DEFRA

A REVIEW OF RESEARCH ON PRESSURE FLUCTUATIONS IN DRINKING WATER DISTRIBUTION SYSTEMS AND CONSIDERATION AND IDENTIFICATION OF POTENTIAL RISKS OF SUCH EVENTS OCCURRING IN UK DISTRIBUTION SYSTEMS

(WT1205 / DWI 70/2/220)

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SUMMARY

I OBJECTIVES

1. Review literature data on pressure fluctuation within drinking water distribution systems;
2. Identify the key features of distribution systems that are likely to generate low and negative pressures;
3. Identify a number of distribution systems in England and Wales where there is the potential for low or negative pressure to be generated and where appropriate models exist to support investigation of this phenomenon;
4. Establish the risks of low and negative pressures being generated in drinking water distribution systems in England and Wales;
5. Propose a methodology, including approximate costing, to conduct pilot studies in the areas identified; and
6. Suggest other possible avenues for research in this area.

II CONCLUSIONS

1. Two mechanisms for producing pressure fluctuations have been identified: 1) pressure transients (surge), and 2) longer-term pressure events caused by exceptional demand (including bursts).
2. There is little evidence in the literature for pressure fluctuations sufficient to cause ingress.
3. Surge effects are of limited size and penetration in distribution systems although they can occur in unbranched trunk mains and in smaller distribution mains close to these trunk mains.
4. Network modelling can be used to identify areas at risk.
5. Network modelling demonstrates that, if exceptional demands are to cause very low pressures, these demands must be very large.
6. Points downstream of the exceptional demand and high points are most at risk.
7. To cause ingress, the high point must be approximately 15 m or more above the demand point.
8. Analysis of pressure monitor data suggests that low pressure fluctuations sufficient to cause ingress will happen 0.23 times per year per 1000 population served.
9. Although these are rare events, the above rate translates into a value of 12000 per year in England and Wales.

10. This project has been concerned with the risk of very low pressure. The risk of this leading to ill-health has not been covered in detail in this report.

11. The literature shows that ill-health can be caused by ingress. Most are linked to intermittent supplies which are not relevant to England and Wales.

12. An approach to pilot studies has been developed but it is thought that these would provide very little direct evidence.

III SUGGESTED FURTHER WORK

1. Pressure logging to provide more data and analysis.

2. The development of a routine modelling approach to identify areas at risk. This could then be used as a survey tool by companies.

3. Develop estimates of the disease burden using Quantitative Microbiological Risk Assessment.

4. Develop estimates of the disease burden using epidemiological studies.

The necessity for items 3 and 4 would depend on the results of earlier items.

IV RESUMÉ OF CONTENTS

This report is primarily concerned with the risk of low pressures being developed. There is a further issue which is not the major concern of this work but which is covered briefly, i.e. if low pressure does occur what is the risk that this has an adverse effect on public health.

Chapter 2 reviews the literature on fluctuation of pressure in distribution leading to very low values. Chapter 3 discusses the mechanisms involved in pressure fluctuation in networks drawing particular attention to the difference between true pressure transients (surge) and slower moving variations in pressure. Chapter 4 (Quantifying the Risk) gives estimates of the number of occurrences of pressure which is low enough to cause ingress. Chapter 5 investigates network behaviour further by the use of network models and suggests approaches to pilot studies. Chapter 6 considers work beyond the scope of this project which would assist in quantifying the risk of ill-health arising from these low pressure events. The report conclusions are in Chapter 7.

1. INTRODUCTION

1.1 Objectives

The maintenance of adequate pressures throughout water distribution systems is an important feature in safeguarding water quality. If the pressure at any point falls to an unacceptably low value, there is a risk of ingress and a consequent risk to health. The primary objective of this work was to investigate the nature of these events and to quantify the risk of such low pressure events happening in England and Wales.

The objectives were to:

1. review literature data on pressure fluctuation within drinking water distribution systems;

2. identify the key features of distribution systems that are likely to generate low and negative pressures;

3. identify a number of distribution systems in England and Wales where there is the potential for low or negative pressure to be generated and where appropriate models exist to support investigation of this phenomenon;

4. establish the risks of low and negative pressures being generated in drinking water distribution systems in England and Wales;

5. propose a methodology, including approximate costing, to conduct pilot studies in the areas identified; and

6. suggest other possible avenues for research in this area.

1.2 Overview

Occasional low pressures in distribution may cause ingress and a consequent risk to health. Two features are necessary to cause unacceptably low pressures to occur: (i) points in the system where the pressures are normally low (though acceptable), and (ii) and event which causes the pressure to fall even further to a value close to (or below) gauge zero. (It should be noted that loss of supply for more than a few minutes has not been regarded in this report as a “pressure fluctuation”.)

This report is primarily concerned with the risk of low pressures being developed. There is a further issue which is not the major concern of this work but which is covered briefly, i.e. if low pressure does occur what is the risk that this has an adverse effect on public health.

Chapter 2 reviews the literature on fluctuation of pressure in distribution leading to very low values. Chapter 3 discusses the mechanisms involved in pressure fluctuation in networks drawing particular attention to the difference between true pressure transients (surge) and slower moving variations in pressure. Chapter 4 (Quantifying the Risk) gives estimates of the number of occurrences of pressure which is low enough to cause ingress. Chapter 5 investigates network behaviour further by the use of network models and suggests approaches to pilot studies. Chapter 6 considers work beyond the scope of this project which

would assist in quantifying the risk of ill-health arising from these low pressure events. The report conclusions are in Chapter 7.

2. LITERATURE REVIEW

2.1 Pressure fluctuation in context

Sadiq *et al*.[1] give (*inter alia*) a good introduction to the components that may lead to ingress of contaminants to water mains. They say that "The vulnerability to (or potential for) intrusion of contaminants in water mains can be evaluated based on the simultaneous occurrence of three elements, a contamination source, a pathway and a driving force. Possible sources … around water mains include sanitary sewers, septic tanks, contaminated soil and water, and high risk service connections." Intrusion pathways (including pipe leaks) occur throughout UK distribution systems. The driving force in this instance is provided when the internal pipe pressure is less than external water pressure.

The concern of this report is pressure and therefore the report primarily addresses just one of the three elements. Even in those cases where the internal pressure is very low, there is a risk of ingress only if there is a local source of contamination and a "pathway" into the pipe.

Finally, if the potable water is contaminated, the probability and consequence in terms of public health depends on further factors (see Section 2.3).

2.2 Pressure fluctuation

There are a number of ways in which contamination can occur. The concern of this work is ingress due to low pressure. Further, the driving force is pressure fluctuation which is taken to mean short term variation in pressure. This limitation rules out some potentially important causes of ingress (mains breaks, repairs and new main installations) which, although they cause pressures to fall, are not classed as "fluctuations". (Disinfection procedures exist and should, of course, be followed when returning mains to service. This approach cannot be used for "fluctuations" away from burst sites since, by their nature, they happen without notice.) However, pressure fluctuations which result from a mains burst and which are located away from the site of the burst are to be included in the considerations.

Pressure fluctuation can be further subdivided into pressure transients (surge) and other short term variation (see Section 3.1).

2.2.1 Pressure transients

Nygard *et al*.[2] say "There are many causes of pressure transients, such as turning on and off a pump, opening and closing valves, power failures, flushing of the network, fire fighting and anything that causes a sudden change in demand. … In recent years, a substantial proportion of waterborne outbreaks have been attributed to failures in the distribution system." However, they then report on a study "to assess the association between mains breaks or maintenance work in the water distribution system with presumed pressure loss and gastrointestinal illness…" These events would not qualify as "transients". It is possible that this kind of linkage between the words "pressure transient" and "incidence of illness" has lead to an exaggerated concern for the risks of pressure transients.

One reason why significant pressure transients may be rarer than is sometimes supposed is given by Sadiq *et al*.[(1)]: "Extreme transient pressures are more typical of long transmission mains and are less likely in the normal operation of an urban distribution network." Again, Boulos *et al*.[(3)], whilst remarking that "Transients….may result in…..the backflow/intrusion of dirty water.", also say "Water distribution systems comprising a short length of pipes (i.e. <2000 ft [600 m]) will usually be less vulnerable to problems associated with hydraulic transient. This is because wave reflections (e.g. at tanks, reservoirs, junctions) tend to limit further changes in pressure and counteract the initial transient effects. A detailed analysis of this issue is given by Stapel[(4)] and is explained in Section 3.2.2.

Gullick *et al*.[(5)] measured pressures at 7 locations for 14 months in a network serving a town of 130,000 population in the USA. Pressure fell below 14m on only 9 occasions with a minimum value of 6m. Transient modelling predicted negative pressures for a case of power failure and a mains break which occurred during the logging period. Unfortunately, no monitor was located in the low pressure areas. (Although later monitoring in the critical areas did not record negative pressures.) There are a number of reasons for treating the modelling results with caution:

1. The network is on a larger scale than UK distribution systems with 19 m of pipe per connection (cf. a typical UK figure of 10-12 m). In the model, the average pipe length was over 500 m. This is an important issue in the development of surge pressures (see Section 3.2.2).

2. The system is fully pumped with source pumps and boosters (A most unusual situation in UK practice.)

3. The power failure cases analysed involved the simultaneous failure of at least 4 pumps.

4. Some crucial assumptions needed to be made including the time taken for the leak to established at the mains break and the wavespeeds appropriate to the pipework.

In a further paper by Gullick *et al*. (Occurrence of transient low and negative pressures in distribution systems.[(6)]) it is noted that "The magnitude of the pressure change can be influenced by system characteristics such as non-networked and dead-end pipelines (which typically would have larger surges than comparable but well-looped areas),….. Pipe leaks and regular water demand can also act to reduce surge magnitude". The work reported in this paper involved high speed pressure monitors at 43 sites in 8 systems. The sites were chosen by a combination of transient modelling and local knowledge to be those particularly susceptible to low surge pressures. The total number of days monitored was 4640. 15 surge events which resulted in zero or negative pressures were recorded. 12 of these were caused by "a sudden shutdown of all pumps at a treatment plant or pump station." It is significant that the monitoring points in these cases were on a very close to a long trunk main. Two examples were the result of the operation of water cannon with the monitors (apparently) close to the hydrant. Monitoring close to specific events such as fire-fighting practice and high demand use did not measure negative pressures.

Whilst this paper reports (a few) negative pressure events, it is significant that most are the result of multiple pump shutdown and are monitored close to a long trunk main. This is not to imply that such events are unimportant but that the parts of the system at risk may be limited. The role of trunk mains in the development of surge and the extent to which pressure fluctuation extends into the smaller mains of a distribution system is discussed in Section 3.2.2.

Negative transient pressures are reported in a paper by Besner *et al.*[7] Eleven negative pressure events were recorded over a 4 month period of monitoring at 12 sites. However, 4 were due to "the closure of the transmission main" and 3 measured in sections that had been isolated for repair. Four were caused by power failure at the treatment plant and were transient pressure events. In monitoring over a further 11 months, 2 examples of negative transient pressures with unknown cause were recorded. The position of these sites in the system is not clear from the paper. (Note. A paper on the epidemiological study to which this paper refers is referenced[19] in Section 2.3.2.)

Fleming *et al.*[8] make some interesting observations about the characteristics which make a site more susceptible to low transient pressures. These include low steady state operating pressures, distance from storage, few loops in the pipework, high elevation, presence of pumps, high pumping velocity, proximity to pumps and the absence of surge suppression. This underlines the necessary coincidence of conditions needed to give a low pressure transient problem.

The authors note that "the surge models would likely over-estimate the severity of surge pressures". Three of the systems modelled in this work were also monitored. A total of 18 sites were monitored for a few weeks. Only one instance of negative pressure was recorded. It was concluded that modelling is useful for locating vulnerable areas.

There are also sections on modelling and monitoring pressure surge in a paper by Kirmeyer *et al.*[9] on pathogen intrusion into the distribution system. Models of three systems showed the potential for widespread low pressures but measurement in two of the systems found no negative pressures. (However, many sites were monitored for just a few days.)

Karim *et al.* report on two aspects[10]. They found that "Indicator micro-organisms and enteric viruses were detected in soil and water samples immediately adjacent to distribution system pipelines." For example, total coliforms were detected in 23 of 33 soil samples. However, negative pressure was measured on only one occasion at one out of 12 sites.

2.3 Epidemiological evidence of health aspects

The evidence for possible health effects of pressure transients comes from various sources derived from both outbreak (large numbers of people affected in a localised area) and not outbreak settings. However, as discussed below, little of this evidence is totally unequivocal.

2.3.1 Outbreak settings

The strongest evidence for health effects linked to low pressure events comes from certain outbreak reports. Most of the more convincing reports come from outbreaks linked to intermittent supplies. Examples of these include:

- The Holy Cross College Football Team outbreak of hepatitis during September and October 1969 which was shown to be due to contaminated water being aspirated into a water supply due to low pressure secondary to high demand as a result of water being needed to control a large fire[11].

- An outbreak of viral gastroenteritis affecting about 1500 people in northern Georgia, US[12]. Low pressure in the potable water distribution system at times of peak demand in a mains

drinking water system allowed water from a more polluted industrial water distribution system to move into the potable supply through an inappropriate connection.

- An outbreak of *Campylobacter* in Sweden that followed in the days after multiple complaints of low pressure at the tap by consumers[13].

- An outbreak of multi-drug resistant typhoid fever in the Kashmir Valley associated with pressure loss in an intermittent supply[14].

More recently in a review of European outbreaks, Risebro *et al*.[15] reported in 2007 that 19 of 61 (31%) outbreaks from 1990 to 2005 with adequate data were attributable to problems in the distribution network. Of these outbreaks two were associated with low pressure events.

2.3.2 Sporadic disease

US workers suggested that low pressure events and low pressure transients could allow aspiration of pathogens into water distribution systems[16] However, compared to outbreak related infections, the epidemiological evidence for sporadic infections being linked to low pressure events is less strong. Hunter *et al.*[17]) analysed data from controls that was originally collected as part of a case control study of sporadic cryptosporidiosis. The authors reported an analysis of the risk factors for self-reported diarrhoea in this group. Of 427 controls, 28 reported having had diarrhoea in recent weeks. The most statistically significant risk factor in the final analysis was also reporting pressure loss at the tap with diarrhoea positive respondents reporting pressure loss some 12 times more frequently than respondents without diarrhoea. However, the authors were careful to point out that the primary study was not designed to test this hypothesis and so caution needed to be made in its interpretation.

More recently still, Norwegian workers[18] reported a cohort study where they followed up communities that had a complete pressure loss with a break in supply either because of maintenance or a mains break. One week after the event people in the effected areas and in control areas were contacted to ask about the presence of diarrhoea. The risk of diarrhoea was higher in the exposed population (RR = 1.58; 95%CI 1.1-2.3). However, as the authors made clear, it was very difficult in this type of study to complete blind respondents and so the potential for some form of recall bias exists.

In both of these previous studies the pressure losses were significant and were in fact discontinuations in actual supply. Whether the conclusions from these studies can be applied to pressure transients is uncertain. In any event the risk from pressure transients must be substantially less than that from disruptions to supply.

Another Scandinavian study, this time a case control study of sporadic cryptosporidiosis, reported that one of the risk factors for infection was average water-pipe length per person from the water treatment works[18]. However, even if this association is real it is not clear what the mechanism would be. Ingress of pathogens into the distribution network secondary to low pressure is one possibility.

So far there have been three large randomised controlled trials of point-of-use water filters and self-reported diarrhoeal disease[19,20,21]. Only the first study by Payment *et al*. in Canada reported increased risk of diarrhoeal illness in the control group compared to the filter group. This Canadian water system was supplied with water from a high quality water treatment plant. The significant association in this study may be because of ascertainment bias as this

was the only study that was not blinded. However, one possibility is that the Canadian system may be prone to pressure problems whilst the other two were not.

In conclusion the available evidence supports the hypothesis that both outbreak associated and sporadic diarrhoeal disease is associated with problems in drinking water distribution. However, the evidence is most compelling for situations where the pressure loss has been substantial especially leading to discontinuation of the supply. Available evidence is consistent with the hypothesis that a disease risk is associated with less severe pressure loss, though this cannot be considered proven at this stage and further studies are needed to resolve this issue. In any event the disease burden attributable to pathogen ingress into drinking water distribution systems as a result of pressure loss is still unknown.

2.4 Quantitative Microbiological Risk Assessment

QMRA has only been applied to potential problems in distribution systems relatively infrequently(22,23). From this work it is still not easy to estimate the disease burden from pressure loss events in distribution. These studies have generally used findings of *E. coli* numbers after events in distribution and then used estimates of pathogen to *E. coli* ratios to estimate potential exposure. A further problem with these studies was obtaining all data on possible contamination events from water utilities. In none of these studies was it possible to obtain adequate data on minor or very short term pressure changes.

3. PRESSURE FLUCTUATION IN DISTRIBUTION

3.1 The mechanisms

Two features are necessary to cause unacceptably low pressures to occur: (i) points in the system where the pressures are normally low (though acceptable), and (ii) and event which causes the pressure to fall even further to a value close to (or below) gauge zero.

Distribution systems are generally designed and operated so that, even at peak times, pressure in the mains at all points remains at or above 15 m gauge. In order for ingress to occur the pipe internal pressure must fall below the external water pressure. Since distribution mains are laid close to the surface, this external pressure is unlikely to exceed 1 m. Any temporary pressure fluctuation must therefore be of the order of 15m to be a cause for concern.

The events fall into two distinct categories:

1. A true pressure transient caused by valve movement or pump switching. This is a short time-scale phenomenon (seconds).

2. An exceptional increase in demand (due to, for example, fire-fighting use, a burst or increased domestic or commercial use), or fall in head at a pump. This will cause longer time-scale reduction in pressure.

These two categories are discussed in the following sections.

3.2 Surge in distribution systems

3.2.1 Background to pressure surge (pressure transients)

When the flowrate in a pipe is changed (due, for example, to pump switching or valve movement) there is a resultant change in pressure. This pressure change can be very large compared with the normal operating pressure of the pipe. Consequently, pressure surge can damage pipes and fittings. However, in the context of this report, it is the potential for severely reducing pressure that is important.

The potential pressure change is given by the Joukowsky relationship[24]:

$$\Delta H = \frac{c.\Delta v}{g} \quad \text{--}(1)$$

where	ΔH	pressure change (m)
	c	wavespeed (m/s)
	Δv	velocity change (m/s)
	g	acceleration due to gravity (m/s^2)

The wavespeed (c) is the speed at which the pressure change travels along the pipe. In plastic pipes is typically 300 to 500 m/s and in metal pipes 1000 to 1200 m/s. The potential pressure change can be estimated by substituting values into equation (1).

Let c = 300 m/s (plastic) or 1000 m/s (metal), Δv = 1 m/s and g = 10 m/s^2. Then ΔH = 30 m for plastic pipe and 100 m for metal pipe. Downstream of a stopping pump, upstream of a pump on start up, downstream of a closing valve or upstream of an opening valve, this pressure change will be negative. There is clearly a potential for very low pressure in these positions where these events occur.

It must be emphasised that equation (1) is a rule of thumb which gives the potential change in pressure. There are many system features which modify this result and can only be taken fully into account by the use of transient analysis software.

When a surge wave reaches a pipe junction, a modified wave travels along each of the pipes which meet at that junction. The magnitude of the pressure change in each pipe is less than that of the “incident” wave. If the pipes are of the similar diameter, the resulting changes are considerably less. The reflected wave which travels back to the point where surge was initiated is of the opposite sign to the incident wave and reduces the pressure change.

An important consequence of this reflected wave occurs if the reflection takes place while the pump is running down or the valve is still moving. In these cases, the reflection limits the pressure change at all points in the pipe by interacting with the incident wave. This is a vital issue when considering surge in distribution.

3.2.2 Distribution system aspects

Short mains

There is no doubt of the destructive nature of pressure surge in simple pumping mains where the pressure change has time to develop. This can happen because the travel time from the pump to the end of the main and back to the pump in a single uninterrupted length of main is similar to or greater than the pump rundown time. This travel time (“pipe period”) is given by:

$$\tau = \frac{2L}{c} \text{---(2)}$$

where	τ	pipe period (secs)
	L	pipe length (m)
	c	wavespeed (m/s)

For example, the pipe period for a kilometre of metal pipe is approximately two seconds. If the pump switching or valve movement takes more than two seconds, the full surge pressure change will not develop.

There has long been speculation that pressure surge in water distribution systems is a cause for concern. The concern has been over the possibility of flow variation disturbing sediment or that high pressures may damage mains. In this report the concern is that low pressure induced by surge may cause ingress. In all these cases, it is the complex nature of distribution systems that mitigates the risk.

Limiting the pressure change

Stapel[4] gives an analysis of surge in short mains. "Short" is defined as when:

$$\frac{2L}{c} \leq t_s \text{ ---------------------------------------(3)}$$

where t_s time taken by velocity change (secs)

For short pipes, the pressure change is given by:

$$\Delta H = \frac{2.L.\Delta v}{t_s \cdot g} \text{ ---------------------------------(4)}$$

Suppose that t_s = 2 secs, c(plastic) = 300 m/s and c(metal) = 1000 m/s, then equation (3) gives L < 300 for plastic pipe and 1000 for metal.

If these relationships hold and Δv = 1 m/s equation (4) gives:

$\Delta H > L/10$------------------------------------(5)

In order to produce a pressure of gauge zero (see Section 3.1) when normal pressure is at least 15 m, a pressure drop of at least 15 m is needed. Equation (5) shows that, to achieve this pressure drop, the pipe length must be greater than 150 m. 150 m of uninterrupted pipe is rare in urban distribution systems. In addition, a pipe velocity of 1 m/s is high, being found in certain pipes at peak times. Therefore, it is likely that far more than 150 m of pipe is needed for large pressure drops to occur.

In conclusion, pressure surge sufficient to cause ingress is likely only in trunk mains and a few lesser mains. In such mains slow valve closure and controlled pump switching is advisable.

3.2.3 The spatial extent of surge effects

The preceding section demonstrates that sufficient surge to produce ingress is only likely to be developed in trunk mains. A further consequence of the attenuation at junctions is the limited spatial extent of the effect. When the incident wave arrives at a junction, only a proportion of the pressure change is transmitted along the other pipes. (If the junction is between three pipes of equal diameter and of the same material, the transmitted effect is 2/3 of the incident effect.)

This happens at each succeeding pipe junction and so limits the area of the distribution system affected. However, if ingress does occur in a trunk main, the number of customers at risk is likely to be large because many will be fed through such a main. This is a different result to that for slowly changing pressure fluctuations which can affect pressures far downstream of the initiating incident (see Section 3.3).

3.3 <u>Exceptional demand</u>

Short term pressure fluctuations can be caused by a number of events. These include change in reservoir level, pump speed control, pump failure, PRV malfunction, exceptional demand by

an industrial customer, exceptional domestic demand, fire fighting, and bursts. However, because a large drop in pressure is needed to cause ingress (Section 3.1), some of these can be effectively ruled out.

A drop in reservoir level of this magnitude is impossible and pump speed variation is an unlikely cause. Pump failure would not affect distribution pressures in gravity systems. PRVs tend to fail open which leads to an increase in pressure over normal conditions. It is unlikely that demand by one customer would be sufficient to cause this magnitude of pressure drop. As a result, the key events in the investigation of this phenomenon are exceptional flows from the network at single points (including fire flows and bursts). These can be grouped together under the term “exceptional demands”.

The way in which exceptional demand affects pressures within the network is described in this section using a simple model. (Figure 3.1)

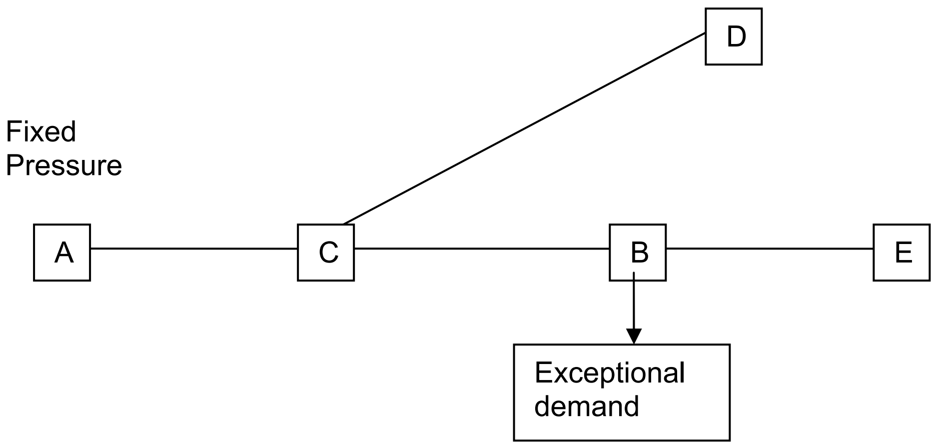

Figure 3.1 Simple network model

“A” represents the source (e.g. service reservoir) as a fixed pressure. An exceptional demand is imposed at B in addition to normal demands. The large flow will increase the friction loss along the route (A to C to B) from source to the demand point and reduce the available pressure by an amount equal to the extra friction loss.

The pipe internal pressure at the exceptional demand point must remain positive in order to drive the flow. (However, negative pressure is possible when the fire brigade uses pumps to draw water direct from the main to fight a major fire.) In fact only in the most extreme case of a catastrophic burst would the available pressure approach zero. Of course, ingress cannot take place in these positive pressure conditions.

To cause ingress at another point in the system, available head at that second point must fall below the external water pressure. For distribution mains, the external pressure is unlikely to be above 1 m. Systems are usually designed to deliver at least 15 m throughout under normal demand conditions. It is clear, therefore, that a considerable fall in pressure (at least 14 m) is required at any point to cause ingress.

It is clear that the risk of ingress is critically dependent on the topography of the system, in particular on the ground level of the point at risk relative to that at the exceptional demand point. Generally, pressure can only fall below gauge zero at points which are higher than the exceptional demand point. In addition to this, points where normal pressures are lowest are at greatest risk.

There are risks from pipes draining down and when mains are returned to service after repair. However, it is argued that these cases are not examples of “pressure fluctuation”. Procedures for disinfecting mains after repair are routine and good practice should be followed.

Network position

Ingress can occur at points with the following relationships to the exceptional demand point: (i) upstream, (ii) downstream, (iii) in a part of the network fed from upstream of the demand point. Pressure at any point in the network is given by the following equation:

$P_N = P_0 + \Delta P_S - \Delta P_F$ --------------------------- (6)

where	P_N	pressure at point in network
	P_0	pressure at source
	ΔP_S	difference in ground level (source minus network point)
	ΔP_F	friction loss from source to point

When an exceptional demand occurs, the only change to the right hand side of equation (6) is an increase in friction loss. The biggest pressure reduction will take place downstream of the demand (section B to E in Figure 3.1). The change in this section will be the same throughout and will be equal to the change at B. (The whole of the friction loss increase from source to point B.)

The change upstream (A to B in Figure 3.1) will be less and will decrease the closer that the point is to the source (A). This is because the friction loss due to the extra flow depends on the distance from the source.

Points in other parts of the system (neither upstream nor downstream of the demand point) can be affected. These areas are those fed from a point upstream of the demand point (e.g. C to D in Figure 3.1). These points will all be subject to the same pressure change as point C.

Model results

In order to demonstrate the importance of ground level a complex profile has been assumed for the model whose schematic is given in Figure 3.1. The long section from source (A) through exceptional demand point (B) to the extreme of the network (E) is shown in Figure 3.2.

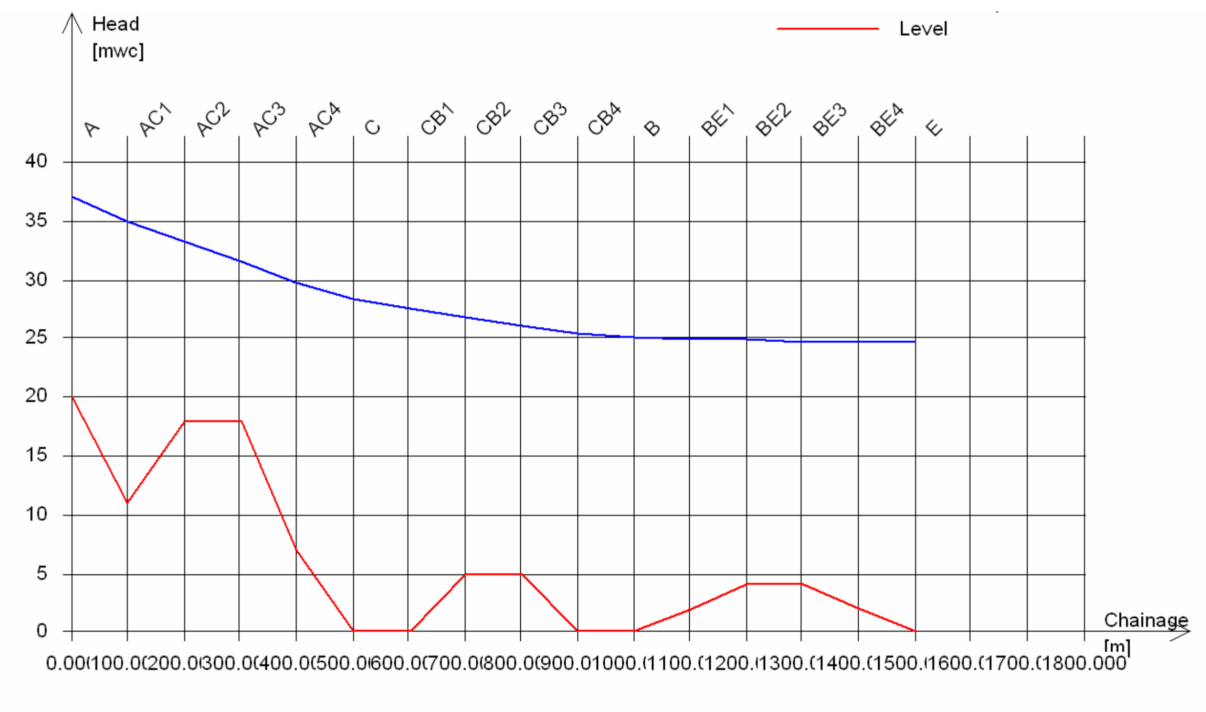

Figure 3.2 Long section from A to E

There are three high points in this diagram. Figure 3.3 is a similar diagram for the pipework from source (A) through the pipe junction (C) to another extreme point (D).

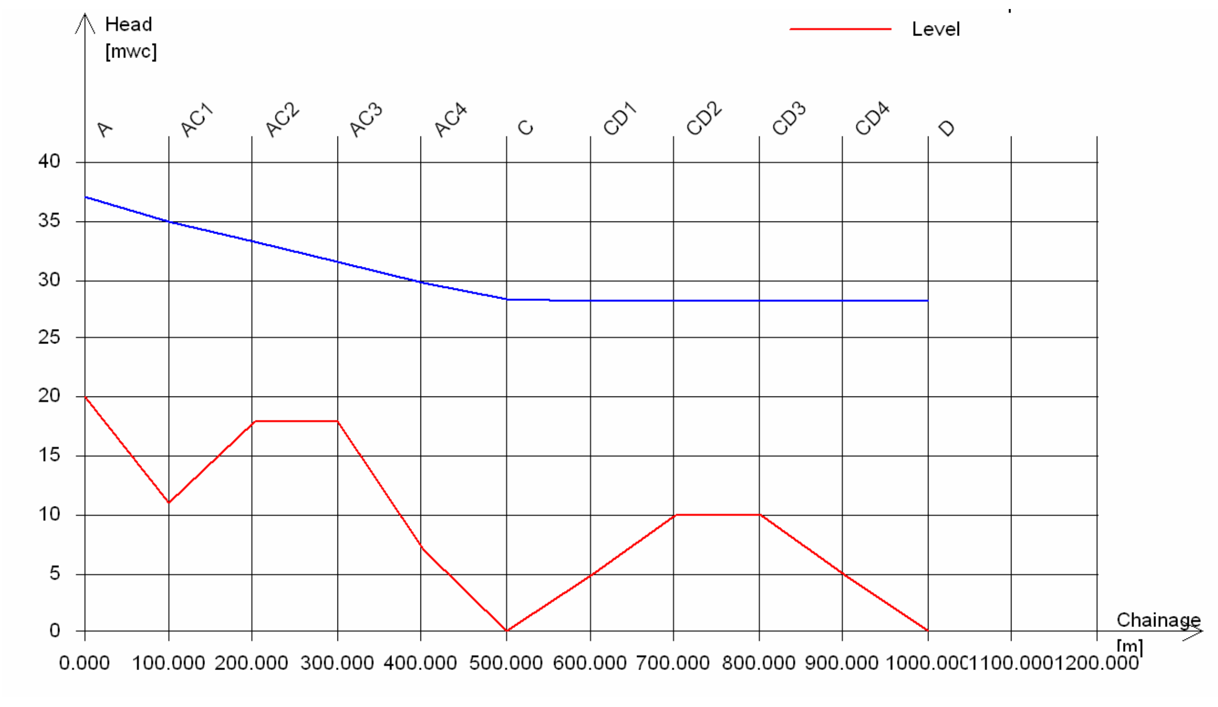

Figure 3.3 Long section from A to D

The model was run for a normal peak time case to produce the pressures in Figure 3.4 and Figure 3.5.

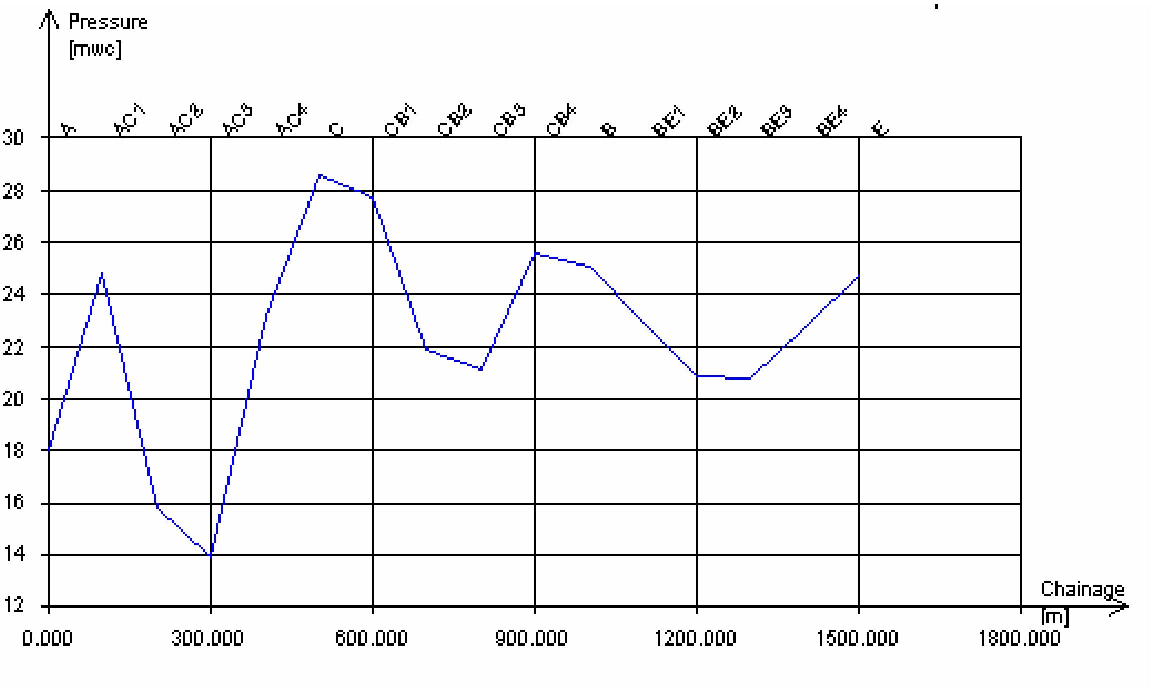

Figure 3.4 Normal pressures : A to E

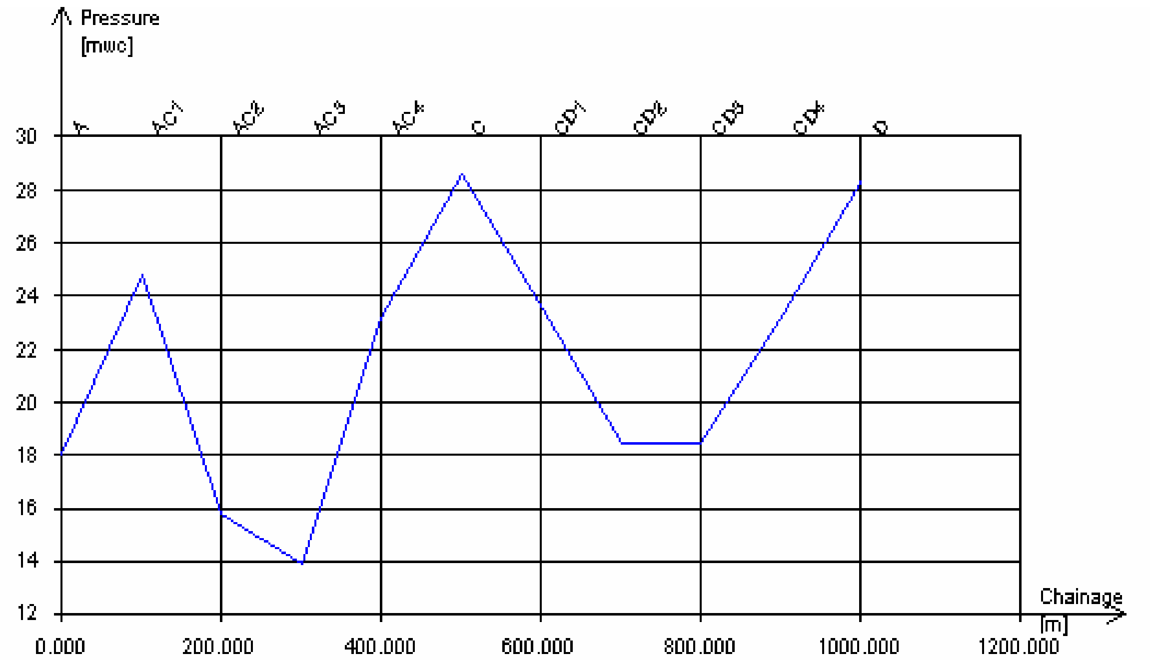

Figure 3.5 Normal pressures : A to D

Pressures are perfectly acceptable except for the marginal value of 14 m at the high point near to the reservoir.

An exceptional demand was introduced at point B. This additional demand is approximately equal to the normal demand on the whole system. It has the effect of reducing the pressure at B by 10 m head. This change impacts on the rest of the system. As suggested above, the effect on points close to the source is small. The pressure at the high point nearest too the source has fallen by less than 4 m to 10 m Figure 3.6. The pressure at the next high point has fallen by 8 m to 13 m. Pressures downstream of the exceptional demand have fallen by the full 10 m.

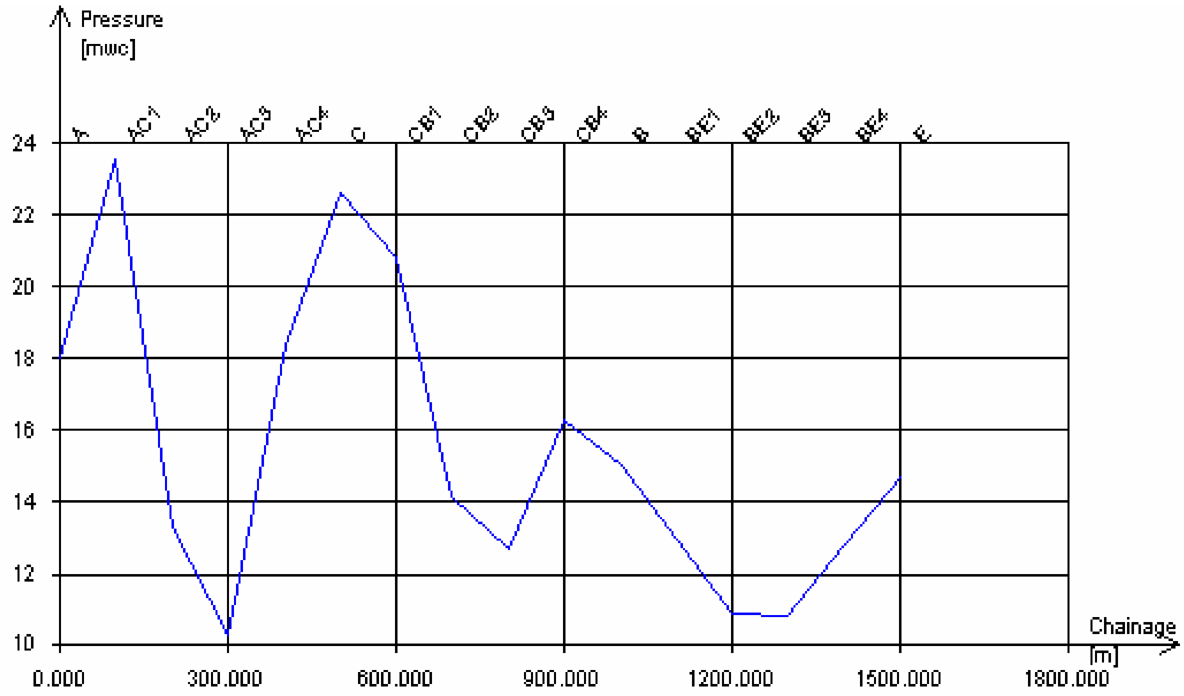

Figure 3.6 Effect of exceptional demand on A to E

Figure 3.7 shows the effect on the pipeline from source to the other extreme point (D). Pressures throughout the leg downstream of the junction (C) have fallen by 6m (the change in friction loss to C.

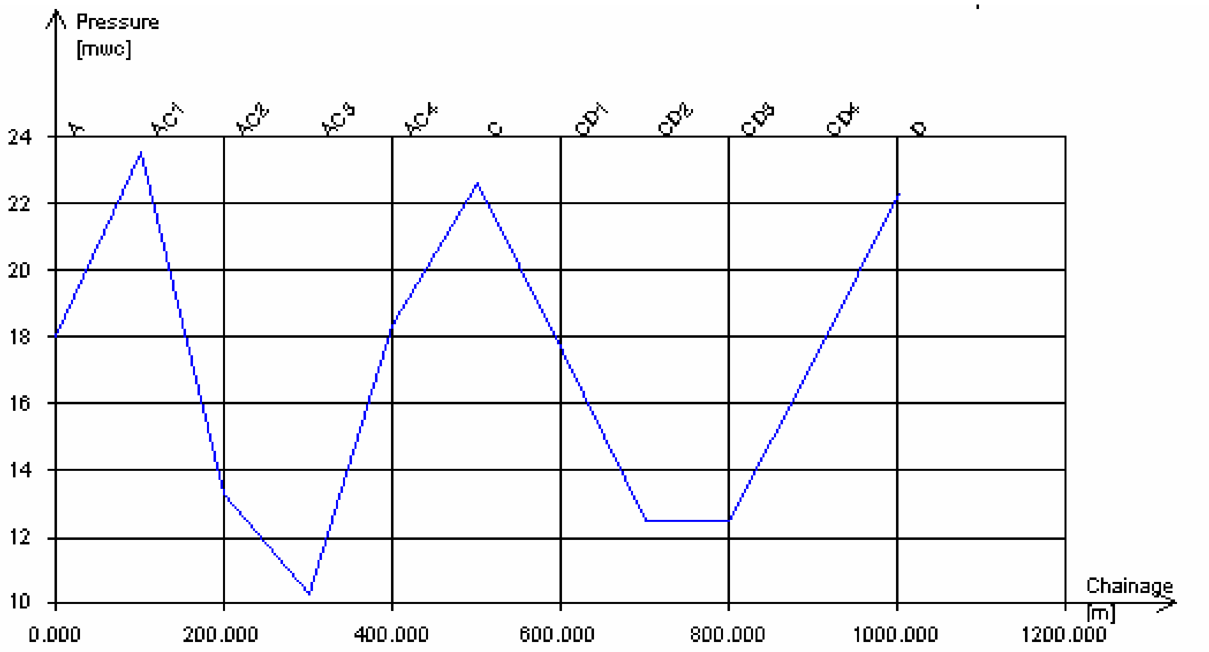

Figure 3.7 Effect of exceptional demand on A to D

The exceptional demand has had a marked effect on system pressures but nowhere has pressure approached a value where ingress is a risk. All pressures are above 10 m.

The exceptional demand was increased so that it was more than twice the previous value (and three times the normal network demand). The results are shown in Figure 3.8 and Figure 3.9.

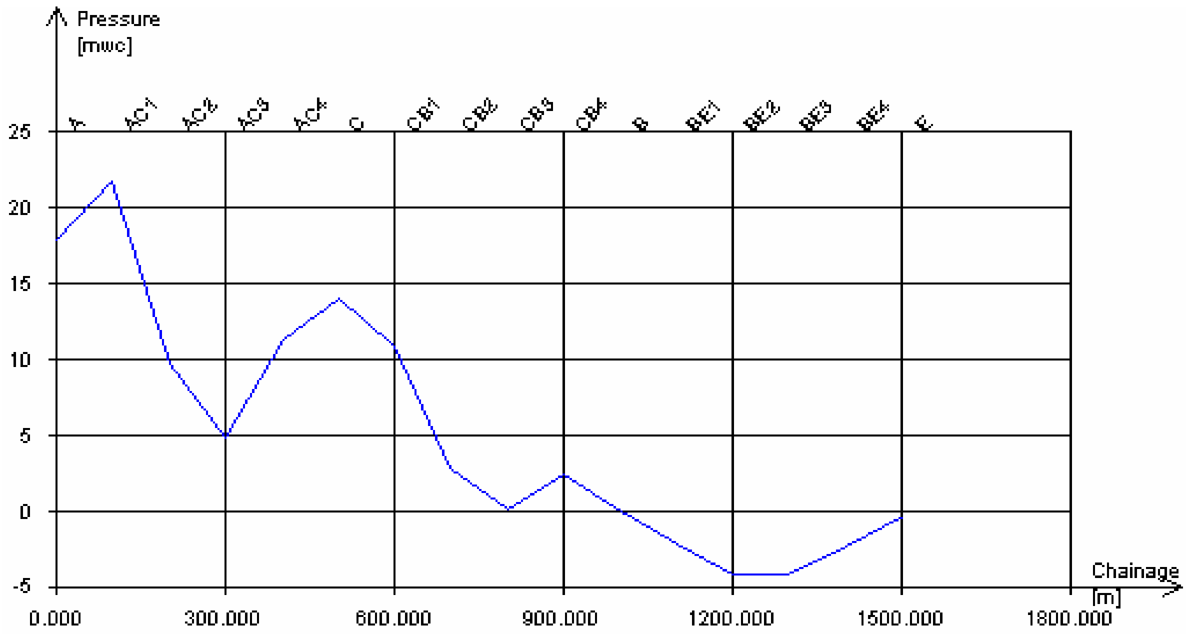

Figure 3.8 Effect of greater demand on A to E

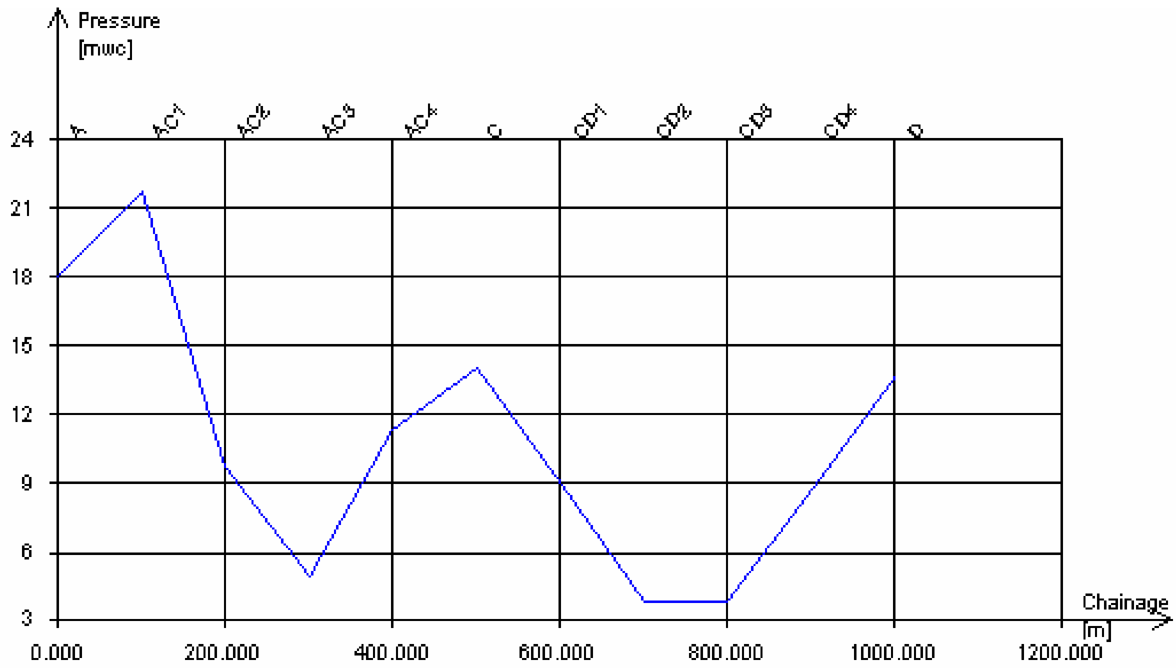

Figure 3.9 Effect of further demand on A to D

Again the event impacts on the whole of the system and again the worst affected area is downstream of the demand. Pressures there are such as to cause ingress (Figure 3.8). Pressure at the high point immediately upstream of the exceptional demand is now zero.

However, in spite of the imposition of this extraordinary demand, pressure at the high point close to the source and in the leg from C to D are significantly above zero.

Indications from model results

The simple model used above is, of course, only an example. However, the pipe diameters, normal demands and friction factors are all reasonable. A number of points are exemplified by the results:

1. A quite exceptional additional load is needed to induce the large necessary large change in pressure.

2. Points downstream of the exceptional load are most at risk.

3. Points upstream of the exceptional demand and those on branches fed from upstream of the demand are affected.

4. High points are most at risk.

In addition it should be noted that:

5. If ingress occurs, all customers downstream of the ingress are potentially at risk.

4. QUANTIFYING THE RISK

4.1 Background to the data

The first approach considered was to calculate the risk by quantifying the mechanisms described in Section 3. This would require information on the nature of distribution networks (e.g. ground levels and normal operating pressures) and the frequency of events that might initiate low pressure fluctuations. This was always going to be a difficult calculation. However, very little data is readily available of the type described and this approach to a national calculation proved totally infeasible.

The author is grateful to all the water company staff who provided insight into this problem. In the event, it was decided to attempt the quantification using distribution pressure monitor data. This is a direct approach to the question “How often do distribution pressures fall to very low values?” However, in practice, it is not straightforward. The difficulties are discussed in the following sections. Three companies were able to provide data. Each was in a different form and the analysis of each is also given in the following sections.

4.2 Pressure data from Company A

4.2.1 Data provided

Company A has 2467 permanently-sited pressure monitors covering the whole of the Company. The sites were chosen to be the pressure-critical points in the area (DMA or pressure management area) that they represent. For the purposes of this work, it is assumed that a count of low pressure events at these points will be representative of all events in the Company.

The minimum pressure for each day of the year 1 July 2006 to 30 June 2007 was provided for 42 monitoring points. The number of occasions when the pressure fell to a very low value was counted.

4.2.2 Analysis

The primary pressure criterion used was “less than or equal to 1 m gauge” (The reasoning is given in Section 3.1). This test found such pressures in 14 of the 42 areas. The results are given in Table 4.1.

Of the selected pressures many could be discarded (see the “Bad data” column in the Table). These fell into two categories; values less than -10m gauge and long series of identical values. This produced the “Good data” column. In four areas, although the low pressure values on consecutive days were not identical, they were also discarded (see the “In blocks” column in Table 4.1). These may also be bad data. Otherwise, they represent days of difficult operation which do not fit the description “pressure fluctuations” as used in this work (see Section 2.2).

Table 4.1 Company A results

Monitor	Selected	Bad data	Good data	In blocks	Events	Days	Comments
1	1	0	1		1	362	
2	2	0	2		2	335	"-5" and "0" on consecutive days
3	54	1	53	53	0	364	53 consecutive days and one < -10
4	17	17	0		0	348	All < -10
5	1	0	1		1	268	"0"
6	26	26	0		0	206	All < -10
7	4	0	4		4	365	All "0"
8	12	0	12	11	1	365	11 consecutive days
9	17	17	0		0	292	Consecutive "0.5"s and blanks
10	89	89	0		0	245	Block of 8 and one of 81
11	54	53	1		1	221	Block of 53 mainly -0.1
12	25	12	13	13	0	352	12 consecutive "-0.3" and a block of 13
13	3	0	3		3	365	2 on consecutive days
14	20	19	1		1	346	19 and 1 "-0.5"

The result of this step is given in the column headed “Events”. There are a total of only 14 events in the 42 areas. Even this may be an overestimate for two reasons; the zeroes may be further bad data and, some of the values selected may be part of a long series for that day and therefore fail the “fluctuations” criterion mentioned above.

Because of missing and bad data, the 14 areas have only 12.15 year’s worth of data. This gives a rate of 16.13 low pressure events per year in 42 areas. However, the Company has 2467 monitors. This suggests a rate for the whole Company of 948 per year.

This can also be expressed as 0.23 low pressure events per year per 1000 population served. (This figure allows a comparison to be made with companies of different size.) This is equivalent to 12000 events in a year for England and Wales.

4.2.3 Discussion

The number of “events” discovered was low (14 in the year). Because of this, the result is very sensitive to the inclusion of spurious events. In this case, it is thought that the most likely reason for an inflated figure is that some of the occasions may be longer term loss-of-supply rather than the “fluctuations” that are the subject of this work.

It must also be remembered that this estimate is concerned with the occurrence of low pressure. The fact that ingress is possible in these cases does not mean that it will happen or that there will be any adverse effect on the consumers.

Further calculations were carried out to investigate the sensitivity of the results to the definition of “low pressure”. It is just conceivable that ingress could occur if internal pipe pressure were as much as 2 m or even 3 m. There were 4 occasions when pressure fell to a value of between 1 m and 2 m and 2 occasions when the minimum pressure was between 2 m and 3 m. These results are interesting for two reasons:

I. These considerable relaxations of the criterion have a fairly small effect on the result.

II. There are fewer events in these categories than in the original. This may be suggestive of bad data or “loss-of-supply” where zeroes have been recorded.

4.3 Pressure data from Company B and Company C

4.3.1 Data provided

Company B has a large number of permanently-sited pressure monitors (1800 as of October 2007). Each is situated at the critical point of a District Meter Area or Pressure Management Area. They plan to install 4500 loggers which will then cover the whole Company area.

Fifteen-minute-average pressure data was provided for some 70 monitors. Typically the data was for a 6 month period.

Company C provided data from loggers which are used for temporary logging at different sites throughout the Company. For 16 sites, the values were 5-minute-averages and for 4 sites they were 15-minute-averages.

4.3.2 Analysis

This project is concerned with short term pressure excursions; the data from these Companies were averages over a longer period (minima were not available). It was therefore necessary to infer the possibility of short term low pressure from the average values.

An analysis technique was developed consisting of two steps:

1) Calculate a rolling average series from the raw data.

2) Search for differences between the raw data and the rolling average sufficient to imply a temporary excursion to a very low value.

This analysis was applied to Company B data with the following variations:

a) The pressure sufficient to cause ingress equal to 1, 2 and 3 m.

b) The length of the low pressure period equal to 1 and 2 minutes.

It became clear that, for many monitors, this approach was flagging large numbers of spurious “events” for a number of reasons. Probably the most important of these being that the data discrimination is inadequate for a subtle calculation.

It was reluctantly accepted that data in the form of average pressures is unsuitable for this investigation. Pressures as short term averages or instantaneous values are needed as in Section 4.2.

The data from Company C was also in the form of average pressures and so no further work was carried out on this data.

5. NETWORK MODELLING AND PILOT STUDIES

5.1 Network model results for a real system

A small (artificial) model was used earlier (Section 3.3) to illustrate some of the more important hydraulic aspects of the problem. A model of an actual distribution system is used here to:

1. amplify these explanations and to introduce other features,
2. demonstrate that the phenomenon can occur in a “real” system”,
3. give a basis for the following discussion of pilot studies.

5.1.1 Cases studied

The relevant part of the system used for this work is shown in Figure 5.1.

The reservoir which feeds this section is shown towards the top left hand corner. Large leaks were introduced, one at a time, in the form of a 50 mm orifice at each of the three positions (L1, L2, L3). The effect at various points in the network was investigated by monitoring pressures at the four points (N1, N2, N3, N4).

Ground levels (g.l.) are given for the 8 positions on Figure 5.1. These show that the area served is very hilly. Example pipe diameters are also given. These range from 12” (close to the reservoir) to 3” at the extremes of the system.

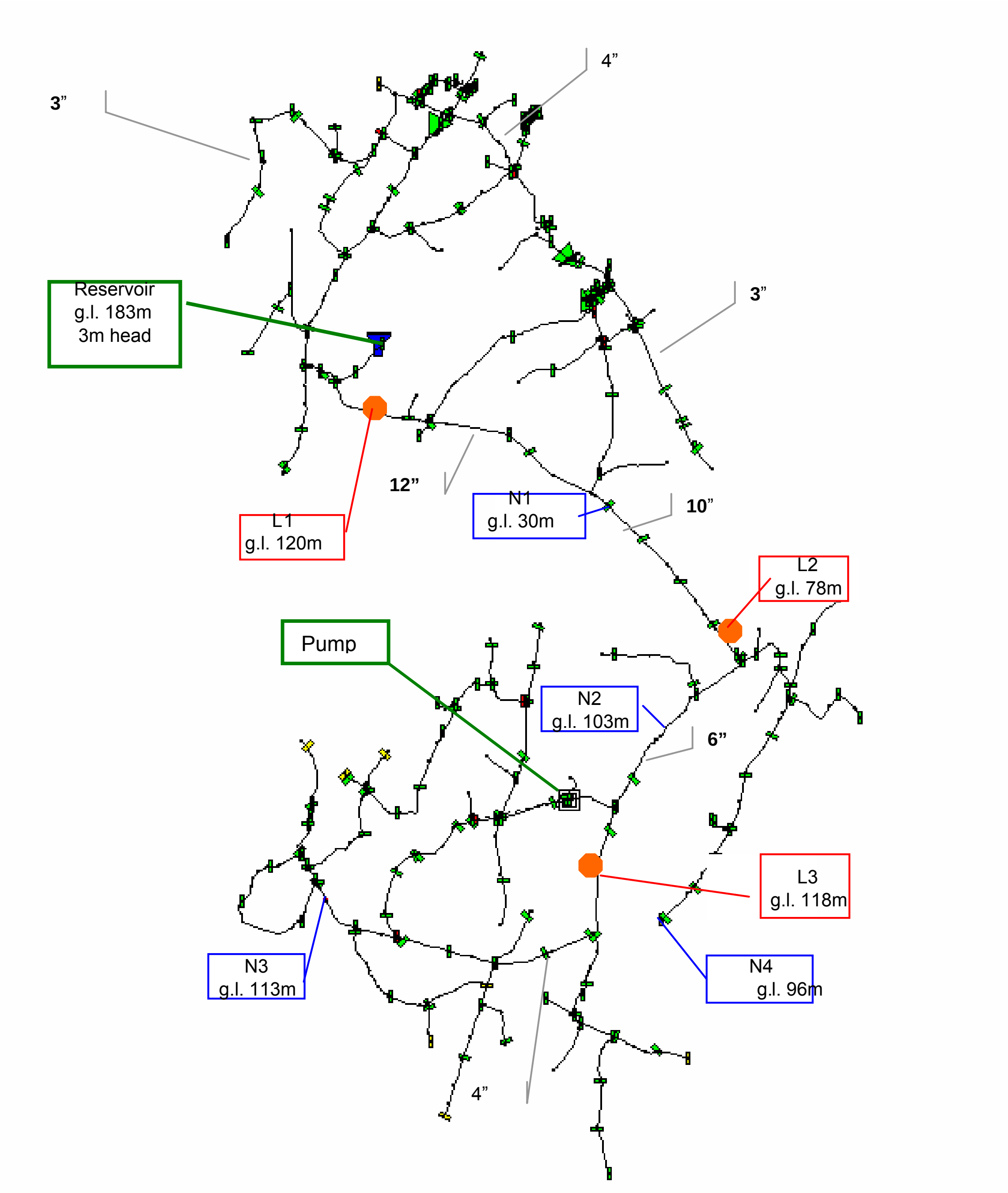

Figure 5.1 Network model schematic

5.1.2 Leak flow rates

These are given in Table 5.1.

Table 5.1 Modelled leak flow rates

Leak position	Flow rate (l/s)
1	40
2	43
3	14

For a given orifice size, the flow rate depends on the difference in ground level between the driving force (in this case a reservoir) and the site of the leak. L1 is close to the reservoir and so the friction loss between the two sites is small. This gives a large flow rate (40 l/s). L2 is further from the reservoir but with a much lower ground level. This gives a high leak rate of 43 l/s. L3 is the furthest from the source and results in a lower flowrate of 14 l/s.

The flow through the leak is by no means the only issue as far as the potential for very low pressure is concerned. This is a complex relationship between size of leak, pipe diameter and length between source and leak and, ground level at other sites within the network. Some insight into these relationships is given in Sections 5.1.3 and 5.1.4.

5.1.3 Effect of leaks in different positions

Table 5.2 shows the reduction in pressure at each of the 4 monitoring points which results from imposing the 3 leaks in turn.

Table 5.2 Reduction in pressure (m) due to leaks

Monitoring point	N1	N2	N3	N4
Leak at L1	4	4	4	4
Leak at L2	14	30	30	30
Leak at L3	4	30	48	7.5

Leak at L1

This has the same effect at all the sites because they are all downstream of the leak.

Leak at L2

All the effects are greater than that due to L1 because of the friction loss in the pipework between the two leak sites. The pressure change at N1 is smaller than at the other sites because it is upstream of the leak. Only part of the enhanced friction loss affects N1. The effects at N2, N3 and N4 are equal because they are all downstream of the leak.

Leak at L3

The reduction at N1 (4m) is smaller than for the case of leak L2 because of the low flowrate at the leak. However, there is a substantial drop at N2 and N3 because the low flow is counteracted by the long lengths of 6" main on the route to the leak and to hence to the two sites. It is, of course, these same high-friction lengths that caused the leak flow to be low. The pressure reduction at N4 is low in spite of its distance from the reservoir because leak L3 is on a different leg to N4. Only some of the enhanced friction loss affects N4 – that up to the common junction of the two legs which is just downstream of L2.

5.1.4 Resulting pressures

Table 5.3 shows the pressures at the 4 monitoring points as a result of the 3 leaks and compares them with normal pressures.

Table 5.3 Pressures resulting from leaks

Monitoring point	N1	N2	N3	N4
Normal conditions	151	73	42	80.5
Leak at L1	147	69	38	76.5
Leak at L2	137	43	12	50.5
Leak at L3	147	43	-6	73

Pressures at N1

Pressures at this point are high because of the very large ground level difference between the reservoir and this point. They remain high in the presence of each of the leaks because the site is supplied by a 12" main.

Pressures at N2

N2 is very much higher than N1: hence the lower pressure in normal operation. L1 has a small effect because of its proximity to the reservoir. L2 is further from the reservoir. L3 is downstream of N2 and thus brings a length of 6" pipe into play. L2 and L3 give a marked reduction in pressure.

Pressures at N3

This point is distant from the reservoir. The resulting pressures are thus entirely dependent on the ground level and the position of the leaks. As the leak becomes more distant from the reservoir, the pressure at N3 reduces until, finally, negative pressure is developed with the consequent risk of ingress. It should be noted that the ground level at N3 is similar to that at L3 giving the enhanced risk of low pressure in that case.

Pressures at N4

This behaves in a similar way to N3 in the cases of leaks L1 and L2. However, the effect at this point of L3 is small because it is fed from a point upstream of the leak and is therefore not affected by the 6" pipework on route to L3.

5.1.5 Area results

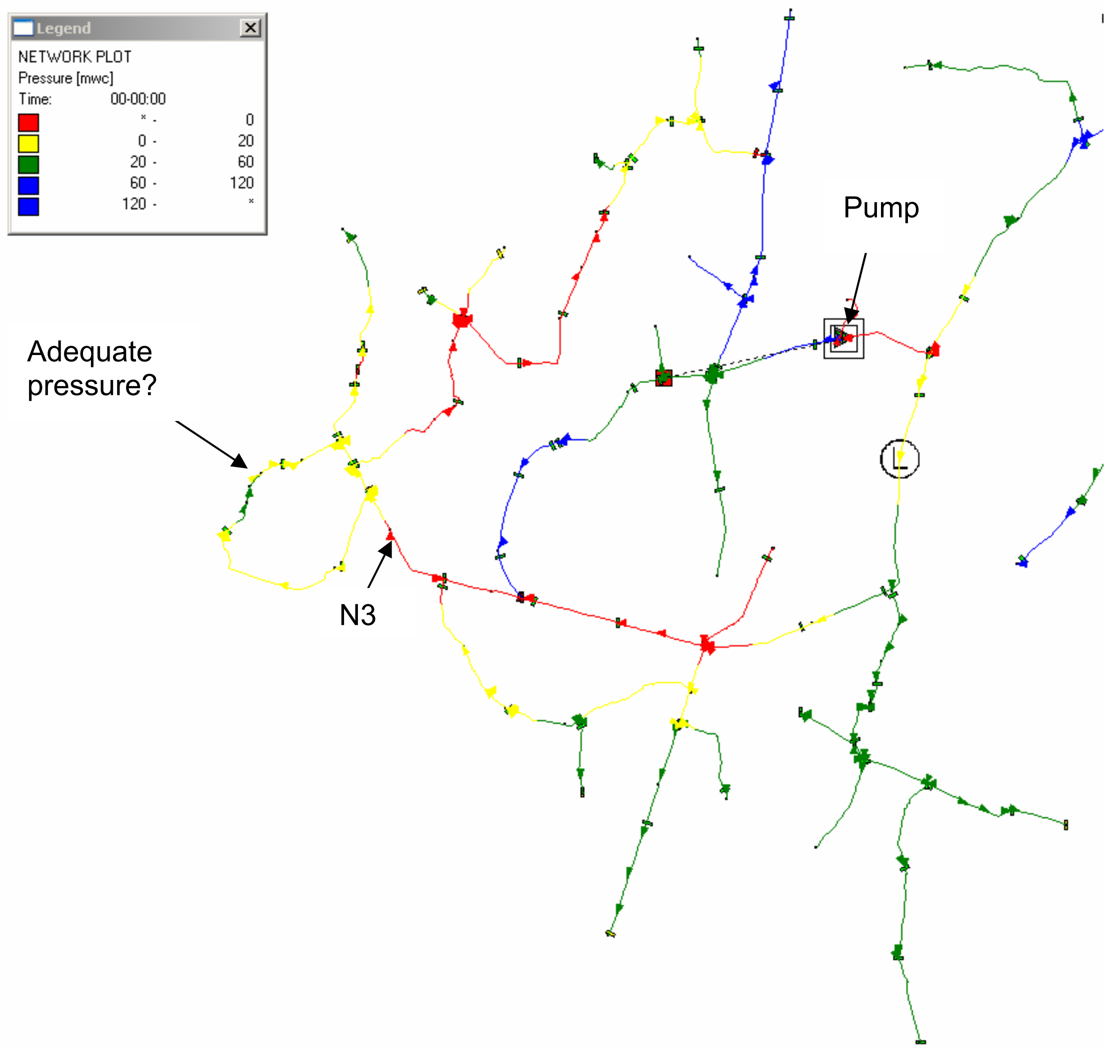

Figure 5.2 The effect of L3 on part of the network

Figure 5.2 shows the effect of L3 on the more southerly half of the system. It demonstrates the crucial role of ground level. The sub atmospheric pressures (red lines) are not at the extremes of the system. An example of this is provided by the monitoring point (N3) used in the above discussion.

Some of the extremes have perfectly adequate pressures (above 20 m). However, these results must be treated with caution. Consider the area to the left of the diagram. The model predicts pressures in the range 0 to 20 m. In practice, in the presence of the upstream negative pressure (and presumed imperfect pipes), it will no longer be supplied by the reservoir. Customer demand will cause this section to drain with the consequent contamination risk. This will take many hours in this instance.

Even if supply is maintained for some time after the burst occurs, customers downstream of the negative pressure region will all be at risk from ingress upstream.

A pump (see Figure 5.2) is necessary to supply part of the area. However, the model shows negative pressures on the suction side. This pump will fail leading to further low pressures.

5.1.6 Models and pilot studies

Network hydraulic models have been used in this report to demonstrate principles and to investigate relevant features of systems in the development of low pressures. They also have a valuable role to play in planning and interpreting pilot studies and this is described in the next section.

5.2 Pilot studies

The two relevant mechanisms have been described in Section 3. One mechanism is surge which produces short term transients and is caused by events such as rapid valve movement or pump switching. The second mechanism produces slower fluctuations and (although there are theoretically a number of possible causes) these are caused by exceptional demands on the system. The two mechanisms are quite different in character and are associated with quite different timescales. Therefore, two different measurement exercises must be considered.

The primary purpose of pilot studies would be verify that low pressures can be developed in real systems as suggested by theory and modelling. The most direct and persuasive way of achieving this would be to model extreme events which produce very low pressures, to impose these events on the actual system, measure pressures at critical points and compare these with model results. The imposed events might be rapid valve closure and running hydrants at high flow rates. It is extremely unlikely than a water company would allow this approach.

A number of less direct approaches are possible:

1. Long term logging to capture naturally occurring events.

2. Pressure measurement during planned events (e.g. fire flow testing).

3. The imposition of less extreme events where the results can be extended by further modelling.

The first approach is considered in Section 6.2. A combination of (2) and (3) is developed below.

5.2.1 Slow fluctuations

Network models for actual systems are a crucial part of this exercise. Systems where all-mains models are available would be used in these studies. The steps are:

1. Model the effects of very high hydrant flow at a number of sites as in Section 5.1. Note positions where very low pressures are predicted.

2. Model the effects of carrying out a fire flow test (acceptable to the Company) at the hydrant sites chosen in step (1). Record the pressure fluctuations at the low pressure sites noted in step (1).

3. Impose the hydrant flows from step (2) on the actual system. Log hydrant flow and pressures at the low-pressure sites whilst hydrant is open.

4. Compare measurements from (3) with results from (2).

5. Revise model if necessary.

Although the pressures measured in step (3) will (by design) be too high to cause ingress, the model/ measurement comparison will be suitable to verify the features discussed in Sections 3.3 and 5.1. These aspects include the roles of: ground level, demand position, flow rate, relationship between demand point and point at risk and, proximity of reservoir.

If a satisfactory correspondence between measurements and model can be achieved, the extension of the argument to unacceptable pressures is persuasive.

The cost of carrying out this type of study is estimated to be approximately £25,000 per distribution system studied plus £5,000 for reporting.

5.2.2 Transients

There is no doubting that pressure surge can generate exceptionally low pressures in the right circumstances. The issue here is whether this can happen in distribution systems and the distance to which any low pressures, generated in this fashion, will travel from the initiating event.

As in Section 5.2.1, it is not necessary to generate unacceptably low pressures to prove the principles. The steps are:

1. Choose pumping stations which each have a different length of uninterrupted trunk main downstream.

2. Choose pressure monitoring sites at the pumping station, on the trunk main and at various points in the network.

3. Record pressures with a high speed logger during pump switching.

Modelling of surge events in large networks is much less of a routine task than steady state modelling. However, a simple transient model of the pumping station and trunk main will show the pressures that would be generated without the interaction with the network.

Although the techniques used in this monitoring and modelling are quite different to those in Section 5.2.1, the cost estimate is the same at approximately £25,000 per distribution system studied plus £5,000 for reporting.

6. POSSIBLE FURTHER RESEARCH

6.1 Pilot studies

Two feasible approaches to pilot studies have been outlined (Section 5.2). However, because system operators are unlikely to allow the imposition of events with potential ill effects on public health, the direct evidence available from these will be limited. There is some value in investigating the extent of surge effects in distribution.

Other valuable research is possible and is outlined below. The need for some of these items is dependent on the results of others. If long term logging (Section 6.2) demonstrates an unacceptable risk of low pressures, then it would be wise to consider QMRA (Section 6.4). If QMRA shows an unacceptable risk of contamination of the water, then the next step would be an epidemiological study (Section 6.5). Because of this interdependency, a detailed budget cost has been developed for the pressure logging but only an indicative cost for QMRA.

6.2 Long term logging

The most valuable data used in this work was from pressure monitors. The minimum pressure in each 15-minute period for a large number of DMAs over a year was available (see Section 4.2). The result would be strengthened if similar data were available from other companies. However, none of the other companies contacted retain data in this form.

A clearer picture and a more secure value for the risk of very low pressures would be obtained by a series of planned logging exercises specific to the investigation of this problem. Two types of exercise are suggested.

6.2.1 Slower fluctuations

1. Select a system with potential for low pressures.
2. Model extreme demands at a number of sites in turn to determine which areas of the system are vulnerable.
3. Site loggers (~20) in the vulnerable areas.
4. Log pressures at 10 second intervals.
5. Download loggers monthly and analyse results. It is estimated that 1 year's logging will be necessary.
6. Obtain data on possible initiating events.

6.2.2 Transients

1. Select a system with potential for low surge pressures.

2. List events which could cause low pressures (probably pump switching).

3. Select sites for loggers (~5) at pumping station, on trunk mains, at sites close to trunk mains and (for confirmation that spatial extent is limited) at sites further from mains.

4. Log pressures at 0.1 second intervals whenever pressure falls below 5 m. Maintain logging for 20 seconds after the initiation of an event. (This interval can be refined on the basis of trunk main length.)

5. (The logger at the pumping station should have the capability to send a text message when an event occurs to allow information on the initiating event to be obtained shortly after.)

6. Check logger and transducer performance quarterly and analyse results. It is estimated that 1 year's logging will be necessary.

More detail is given in Appendix A.

6.3 Use of models by water companies

Network models are available for most areas. This work has shown that they can be used to discover which areas are at risk from low pressure leading to a risk of ingress (Section 5.1).

In principle, a supplier could investigate all areas by this method. However, work is needed to develop the approach so that it becomes a practical, cost-effective method. It is proposed that this development is carried out.

1. Obtain all-mains network models (~3) from a number of companies. These to be systems with apparent potential for very low pressures.

2. Run each model with maximum hydrant flow at each of a large number of sites in turn.

3. Using the results from (2), develop a method for choosing a lower number of sites.

4. Develop tests to quantify the risk and identify the areas at risk.

5. Codify the procedure.

6. Investigate the development of a method to choose systems where this modelling procedure is necessary.

6.4 Quantitative Microbiological Risk Assessment

Quantitative Microbiological Risk Assessment (QMRA) is a modelling technique used to estimate pathogen numbers or predict health effects in a particular situation that has originated from a defined source of contamination. The framework for the model is based on the source-pathway-receptor (SPR) approach. This determines the fate and behaviour of pathogens along the pathway which links the source with the assessment end point or receptor.

Suitable data are fitted to the model to derive an estimate for the numbers of pathogens passing from one stage to the next along the pathway from the source to the specified end-point. The robustness of the assessment depends on the quantity and quality of the data.

This technique is considered useful in those situations where epidemiological studies are likely to lack the sensitivity to detect subtle health effects. It can also be used to identify the particular risk factors and act as a precursor to setting up a more focused epidemiological investigation.

In this context, QMRA offers a useful approach for estimating the health risks associated with short term pressure loss and pressure transients in a water supply. The process giving rise to pathogen intrusion in water mains has three components, all of which must be in place otherwise the process cannot happen. These components are:

1. A source of pathogens surrounding water mains,

2. A point of entry into a pipe, and

3. A force to drive the process.

Each one of these components is looked at in more detail in the following sections to illustrate the sort of information that is required to compile a QMRA.

6.4.1 Deriving an estimate of pathogen numbers surrounding a water main

The ideal requirement is for UK data on the numbers of pathogens likely to be of interest surrounding the buried water mains. However, it seems unlikely that this sort of data exists. A survey conducted in the USA offers some indication of pathogen numbers based on sampling soil and water in the vicinity of water mains, and would be a useful starting point. However, this observation would need to be viewed in the context of the UK situation to ascertain whether water mains would encounter similar levels of contamination.

Where sufficient and reliable data are hard to come by, the boundary of the risk model could be extended to determine pathogen numbers surrounding a water main by modelling the sequence of events giving rise to contamination. The two principle sources are:

- movement of pathogens through soil originating from contamination events at ground level, and

- a leaking sewer pipe whereby the potential exists for movement of pathogens towards a water main.

Both these scenarios require additional data to derive a quantifiable estimate of pathogen numbers. Obtaining this sort of data or making estimates would greatly reduce the accuracy of the predictions as more uncertainties have to be taken into account.

A relatively large amount of data are available on pathogen movement through soils but would need to be combined with information on the type and amount of ground level contamination and the extent to which pathogens are present and would migrate through soil. For the second source of contamination, the extent of leaking sewer pipes could be estimated and combined with an assessment of the likely pathogen numbers reaching a water main.

6.4.2 Deriving an estimate of the integrity of water mains

Various points of entry may exist into a water main. These could arise in older water mains made of cast iron where corrosion has lead to pinhole openings in the pipe. Alternatively, pipes of any material type may have seals and joints which are not intact.

In the absence of actual data, an estimate of pipeline integrity would have to be made on the basis of a qualitative assessment of the condition of company pipeline stock.

6.4.3 Deriving an estimate of the driving force

This report gives an estimate of the frequency of low pressure events as 0.23 per 1000 population per year (Section 4.2.2). However, to drive the process, the pressure difference between the inside and outside of the pipe must be of sufficient magnitude to draw any surrounding water into a main.

The extent of intrusion would depend on the difference between the external pressure surrounding a water mains and its internal pressure. A reasonable estimate can be derived for the range and extent of internal pressures. An assessment of the external pressure could be estimated based on typical conditions for pipe depth and the surrounding water table.

Assessment

A QMRA model to estimate contamination events could be put together based on an assessment of each of the three steps in the process. The derived prediction could be used to make an estimate of the situation nationally or used to estimate the condition locally depending on the choice of the terms used in the model.

The resultant QMRA model is likely to be extensive and subject to a certain amount of uncertainty. However, such an approach often provides a valuable means of highlighting shortcomings in the availability of good quality data. This enables any additional work to gather more data and improve the robustness of the model to be targeted where it is most needed. Additionally, the QMRA approach can inform the decision making process and therefore help to focus more effectively any subsequent epidemiological study.

It needs to be borne in mind that, whilst the QMRA model addresses the likelihood of pathogen contamination of water mains, a further sequence of events would need to be examined to determine impact on public health. Infection would require individuals being exposed to sufficient numbers of pathogens. This would depend on the extent of the protective effect of the disinfectant residual towards each pathogen, the dilution from the water in the supply, the amount of cold un-boiled tap water consumed by an individual and the dose-response relationship for each particular pathogen.

The proposed QMRA will estimate the likelihood of pathogen intrusion into a water main. However, further steps would be required to develop a model which would determine the impact of these events on public health. A greater amount of uncertainty would exist especially regarding formulating suitable dose-response relationships. However, any further assessment may be best approached by an epidemiological study once the outcome of the QMRA is known.

6.4.4 Cost estimate

It is estimated that the cost of a QMRA to predict pathogen intrusion (as detailed in Sections 6.4.1, 6.4.2 and 6.4.3) would be between £15k and £20k. This would be a desk study using existing data.

The outcome of this assessment would determine whether further work, either additional QMRA or an epidemiological study, is justified.

6.5 Epidemiology

Further research may be needed to test the hypothesis that pressure loss events in distribution systems pose a risk to human health, though the exact quantification remains in doubt. Further epidemiological research could confirm the association of diarrhoea with pressure loss events. Such studies could be designed around cohort studies comparing ill health of populations living in areas supplied by water systems known to be prone to pressure loss events with populations living in areas not so affected. Alternatively, time series studies could be designed in areas known to suffer intermittent pressure loss. However, epidemiological studies are only likely to be particularly valuable for larger events that are well recorded and lead to demonstrable changes in human health.

7. CONCLUSIONS

1. Two mechanisms for producing pressure fluctuations have been identified: 1) pressure transients (surge), and 2) longer-term pressure events caused by exceptional demand (including bursts).

2. There is little evidence in the literature for pressure fluctuations sufficient to cause ingress.

3. Surge effects are of limited size and penetration in distribution systems although they can occur in unbranched trunk mains and in smaller distribution mains close to these trunk mains.

4. Network modelling can be used to identify areas at risk.

5. Network modelling demonstrates that, if exceptional demands are to cause very low pressures, these demands must be very large.

6. Points downstream of the exceptional demand and high points are most at risk.

7. To cause ingress, the high point must be approximately 15 m or more above the demand point.

8. Analysis of pressure monitor data suggests that low pressure fluctuations sufficient to cause ingress will happen 0.23 times per year per 1000 population served.

9. Although these are rare events, the above rate translates into a value of 12000 per year in England and Wales.

10. This project has been concerned with the risk of very low pressure. The risk of this leading to ill-health has not been covered in detail in this report.

11. The literature shows that ill-health can be caused by ingress. Most are linked to intermittent supplies which are not relevant to England and Wales.

12. An approach to pilot studies has been developed but it is thought that these would provide very little direct evidence.

13. A staged approach to further work has been suggested: 1) pressure logging and analysis, 2) the development of a routine modelling approach to identify areas at risk, 3) Quantitative Microbiological Risk Assessment, and 4) epidemiological studies.

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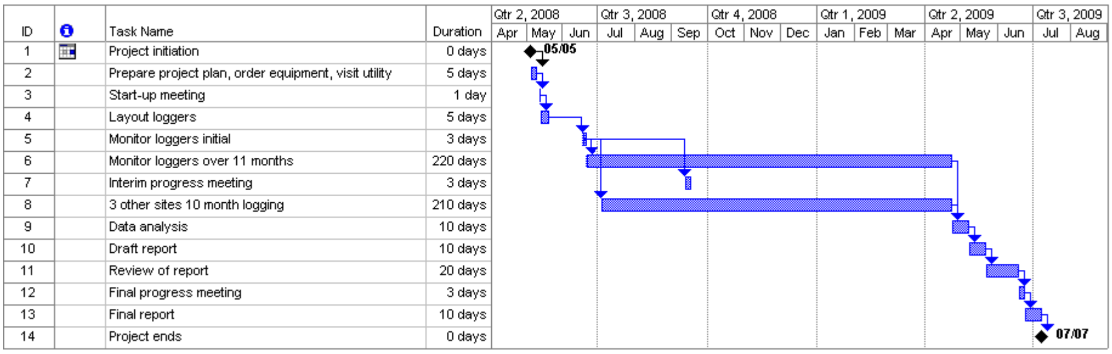
APPENDIX A OUTLINE PLAN FOR PRESSURE LOGGING

A1 SURGE DERIVED EVENTS

Following the procedure in Section 6.2.2, a set of five sites in a distribution system would be identified as likely to lead to occasional transient events where the pressure falls to very low levels. Once the sites had been inspected by the research team and the sites agreed with both DEFRA and the utility, logging would commence with an initial month's data being analysed to check that all the equipment is working.

Loggers would be set out in the pumping station and at four other points some distance from the station where the low pressures would be expected to be sub-atmospheric. The specialised loggers would monitor continuously but only be triggered to record when the pressure fell below 5 m. Using a rolling buffer, the log would start 60 seconds before the trigger and continue during the remaining period of the event.

The project would be subject to review, i.e. if several events occurred within a short period, it would not be necessary to continue monitoring as sufficient data had been obtained. The expected work programme is shown below.



The project would be as set out in the table below.

Activity	Duration
Prepare project plan, order equipment, visit utility Start-up meeting with utility and DEFRA Layout loggers at first site Monitor loggers to check initial operation	1 week 1 day 1 week 3 days
Monitor loggers over 11 months and check quarterly Interim progress meeting Data analysis Draft report	11 months 3 days 10 days 10 days
Review of report by DEFRA Final progress meeting Final report	20 days 3 days 10 days
Total	Up to 14 months

A2 SLOWER FLUCTUATIONS

The procedure for the slower fluctuations would follow that of the surge derived events with the following differences:

- There would be more loggers (20 No) than in the case of the sites where transients were expected as it is more difficult to pinpoint likely places where very low pressures may occur.

- Pressures would be logged at 10 second intervals. A year's logging would be necessary in order to capture sufficient events. However, with a 10 second interval, loggers are readily available which will hold one month's data. The cost-effective option is therefore to use 80 loggers and to download these every month. (This extra work adds to the cost.)

Carrying out both sets of investigation simultaneously would benefit the management and reporting aspects leading to a 10% reduction overall. In the case of both projects, if sufficient events were noted after a shorter period the project could be curtailed.