How the impacts of burst water mains are influenced by soil sand content

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Abstract. Society relies on infrastructure, but as infrastructure systems are often collocated and interdependent, they are vulnerable to cascading failures. This study investigated cross-infrastructure and societal impacts of burst water mains, with the hypothesis that multi-infrastructure failures triggered by burst water mains are more common in sandy soils. When water mains in sandy soils burst, pressurised water can create sub-surface voids and abrasive slurries, contributing to further infrastructure failures. Three spatial data investigations, at nested scales, were used to assess the influence that soil sand content has on the frequency and damage caused by burst water mains 1) to roads in the county of Lincolnshire, 2) to other proximal water mains in East Anglia, and 3) to other proximal infrastructure and wider society across England and Wales. These investigations used infrastructure network and failure data, media-reports and soil maps, and were supported by workshop discussions and structured interviews with infrastructure industry experts. The workshop, interviews and media reports produced a greater depth of information on the infrastructure and societal impacts of cascading failures than the analysis of infrastructure data. Cross infrastructure impacts were most common on roads, built structures and gas pipes, and they occurred at a higher rate in soils with very high sand contents.

1 Introduction

The socio-economic and physical wellbeing of society is increasingly dependent on infrastructure services (Lloyds Register Foundation, 2015; Guikema, 2015; Defra, 2013). Infrastructure assets (e.g. pipes, cables, roads, substations, pumping stations and buildings) are commonly co-located, so a failure of one asset (e.g. a burst water main) may lead to failures in proximal networks (e.g. damage to a road, and/or flooding of gas networks). Complex infrastructure failures can be cascading, escalating or have a common cause (Rinaldi et al. 2001). They can occur at a range of spatio-temporal scales and affect both physical and socio-political infrastructure.

Multi-infrastructure failures often result from a single failure in the crowded and heterogeneous array of co-located, aged and modern, interconnected and semi-automated infrastructure systems (Pritchard et al. 2014a). These systems operate with physical, geographic, functional, cyber, policy, and informational dependencies and interdependencies (Rinaldi et al., 2001; Zimmerman, 2004; Dudenhoeffer et al., 2006). These close relationships can make infrastructure vulnerable to complex failures. Potential for the initial infrastructure failure is influenced by both inherent infrastructure factors (e.g. for water mains, these may include: age, material, diameter, joint technology, workmanship, co-location, pressure management, investment) and environmental factors (e.g. soil, vegetation, extreme or rapidly changing weather). Rapid or extreme environmental changes often expose the vulnerabilities of aging and deteriorating infrastructure networks.

An example of how burst water mains can impact on other infrastructure networks occurred in Matlock, Derbyshire, UK, (Appendix A; ref 32). Here, flooding from a burst main closed two roads, disrupting transport across the city. Escaping water formed a void under the road surface, into which a water-company van fell, fracturing a gas main. The gas leak forced the evacuation of 25 homes, water and sediment flooded the gas network, the County Hall suffered flood damage (including to official records) and was closed for days. This single burst damaged roads, gas networks, and buildings. It impacted government functions and required police and fire service resources. Whilst direct costs of this complex failure totalled many tens of thousands of pounds, indirect costs to society were much higher.

Risks to infrastructure assets represents a key strategic risk for the water sector, and the heterogeneity of infrastructure assets, networks and the soil environment, in which they are buried, produces complexity for infrastructure operators and regulators tasked with providing robust and resilient levels of service (Rinaldi [1]et al., 2001; Rogers et al. 2012; Chalker et al., 2018). With the limited awareness amongst infrastructure asset managers of system-of-systems thinking, which is rarely employed in asset risk assessments, and the limited communication between operators, governments and regulators, understanding of infrastructure interdependencies is often lacking (Young and Hall, 2015; Defra, 2011; Jude et al., 2017; Street et al., 2017; Committee on Climate Change, 2017). Indeed, the second UK Climate Change Risk Assessment (CCRA) identified cascading infrastructure failures as the highest risk facing UK infrastructure (Dawson et al., 2016). Furthermore, the CCRA recommends greater consideration of subsidence risks to infrastructure, and improved risk-information sharing between infrastructure operators (Dawson et al., 2016).

One significant challenge associated with developing an understanding of such infrastructure risks is that natural hazards to the built environment have different frequencies, impacts and spatio-temporal scales. In particular, whilst a considerable body of literature exists surrounding acute environmental hazards such as flooding (e.g. Bowering et al, 2014), less research explores more complex, and often chronic, forms of soil-related natural hazards and related infrastructure failures (Defra, 2011). Such hazards pose substantial risks to infrastructure systems that may be currently underestimated by stakeholders. Because risk-

1

perception is often linked to past experience (Taylor et al. 2014), the impact of low-frequency events with moderate-high impacts may be underestimated by infrastructure operators, as they may not be high on organisations' risk registers.

Soils support infrastructure, yet some soils are prone to forms of ground movement including clay shrink-swell, sand washout, and peat shrinkage (Pritchard et al., 2014a; 2015a, 2015b). While the process of clay related soil movement is relatively well understood, little is currently known about the likelihood of complex infrastructure failures resulting from water pipe bursts in soils with different sand contents. Of particular concern are sandy soils with greater than 70% sand-sized particles (0.06-2mm). Whilst sandy soils cover less than 20% of England and Wales, they are susceptible to water-assisted erosional processes and are not uncommon in some urban settings (Brink *et al.* 1982; Cranfield University, 2016). Thus, water escaping from buried pipes can form voids, removing the structural support normally offered by soil to infrastructure (bridging). In addition, sand and pressurised water can form abrasive slurries which are highly damaging to proximal plastic pipes (Majid et al., 2007).

This paper presents an interdisciplinary scoping study exploring the influence of sandy soils on the impacts of burst water mains on physical infrastructure (electricity, natural gas, water, wastewater, transport and telecoms), public service infrastructure, (government, emergency services, healthcare and education) and wider socio-economic functions. The hypothesis is that sandier soils are more likely to give rise to multi-infrastructure failures due to their non-cohesive structure (leading to void formation) and composition of large, abrasive particles that, under the release of high pressure water, can damage proximal infrastructure. A mixed methods approach is used to help understand the wide-ranging impacts of these events. Four methods and multiple sources of evidence are used. Discussion focuses on the impacts of burst water mains on infrastructure systems and wider society.

Three spatial data investigations, at nested scales, were used to assess the influence that soil sand content has on the frequency and level of damage caused by burst water mains: 1) to overlying roads in the county of Lincolnshire 2) to other proximal water mains in the Region of East Anglia, and 3) to other proximal infrastructure and wider society across England and Wales (Figs. 1 & 2). Lincolnshire is found within East Anglia, which is in turn found within England (Fig 2). In addition, both a series of one-to-one interviews and a joint workshop with infrastructure practitioners were used to elicit expert industry knowledge of the impact of burst mains on infrastructure systems and wider society. The choice of the different study areas was guided by the availability of data of sufficient quality and quantity.

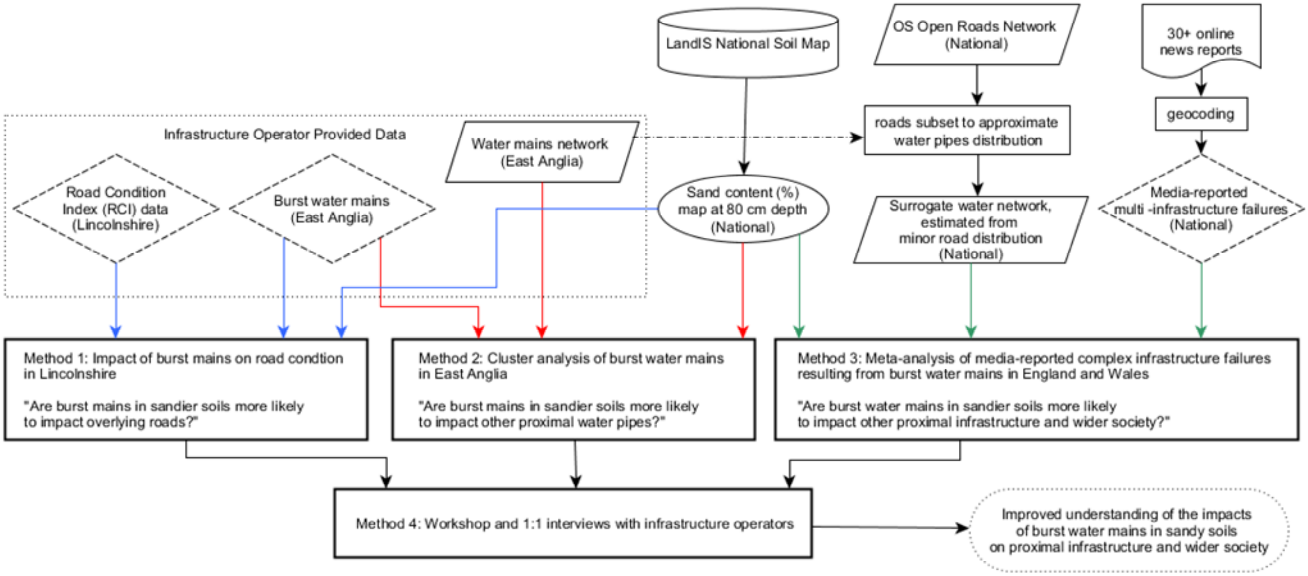

Figure 1 - The flow of data and information between the methods

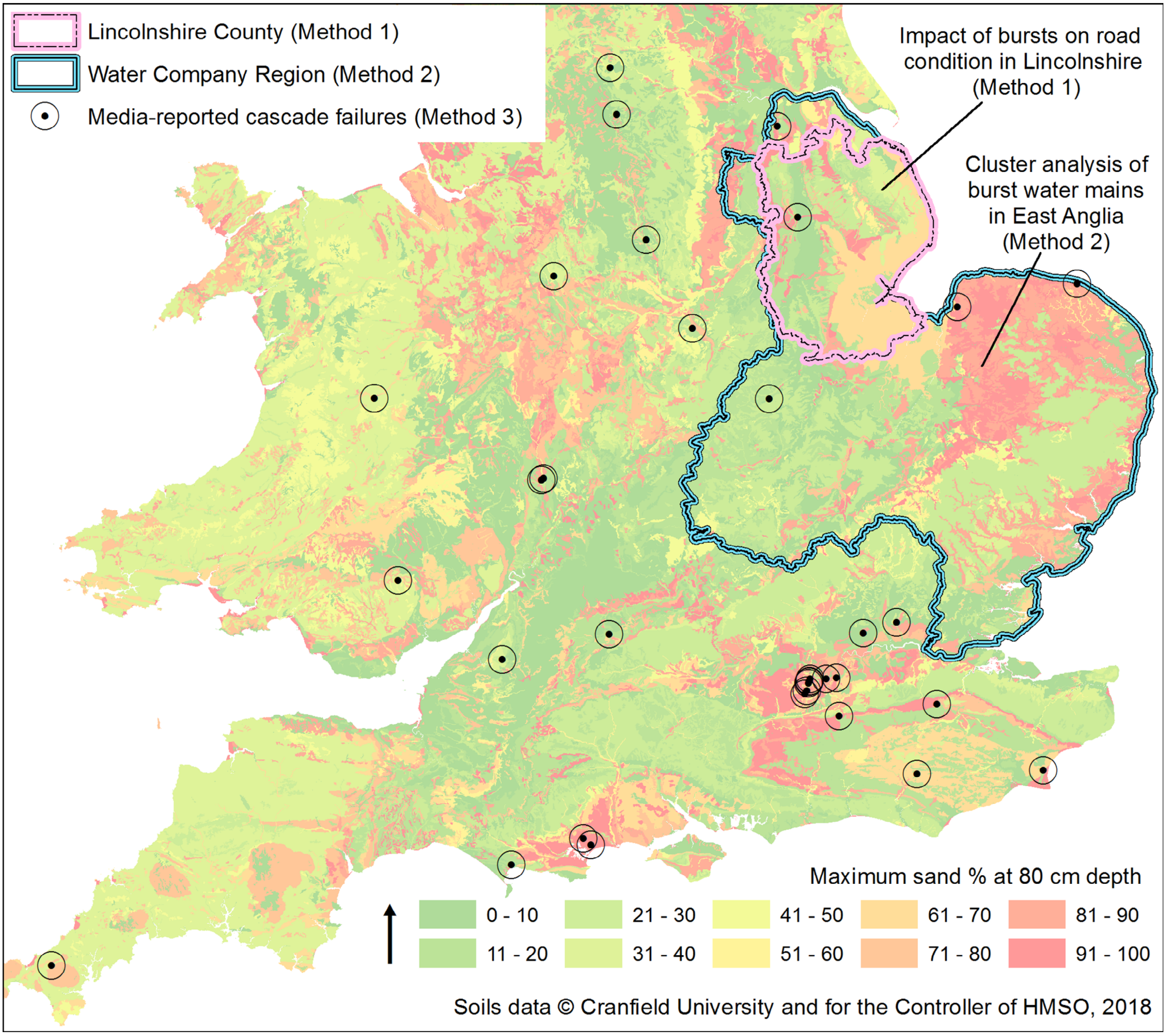

Figure 2 – Map of maximum sand content at 80 cm depth for England and Wales, with the study areas for the different methods, and media-reported cascade failures, which are described in detail in Appendix A.

5

2 Data

This study required data on 1) the distribution of infrastructure networks, 2) the location of infrastructure failures and 3) the related soil conditions. Nine datasets were collected and used in exploratory data analysis, but only six were sufficiently complete, consistent and coherent with the failure mechanisms under investigation to warrant their inclusion in the full study. Industry-provided datasets that were not used included electrical faults data (which was sparse and lacked accurate spatial location) and the sewer network data and sewer failures data (which lacked accurate dates of failure, and in addition, most failures reported were blockages, which lack a strong mechanistic link to burst water mains). The flow of data through the methods is described in Figure 1 and the locations of the smaller study areas are shown in Figure 2.

2.1 Infrastructure network data

In order to calculate rates of infrastructure failure, it was necessary to know the location and lengths of infrastructure networks. Road network data was available for England and Wales from the Ordnance Survey OpenData (OS, 2016). The water mains network (length approximately 43,000 km) was available for East Anglia. Because the entire water network for the England and Wales was not available, it was necessary to approximate the location of the national water network. To do so, a comparison was made of the road network data and water mains data in East Anglia. The length of water mains in each soil map unit across the UK (Fig. 2) was then estimated using the “A”, “B” and “Unclassified” roads from the OS Open Roads data (OS, 2016) as a surrogate for national water mains. In East Anglia, this estimate results in a 7% underestimate of the length of pipe (39,669 km roads vs 43,000 km pipes). This error is sufficiently small for the purposes of this research, and no spatial bias in the linear infrastructure data was observed. In addition, as the water mains data contains additional small lengths of “non-mains” pipes to hydrants and washout legs, the actual underestimate of mains pipes may be less than 7 %.

2.2 Infrastructure failure / condition data

Three types of infrastructure failure / condition data were used in this study. 1) *Road Condition*: Road Condition Index (RCI) data describing the quality of the road surface was available for the County of Lincolnshire between 2008 and 2013. 2) *Burst Water Mains*: The location and reported dates for 50,901 burst water mains between 2004 and 2016 were available for East Anglia. 3) *Multi-Infrastructure Failures / Societal Impacts*: 33 media-reported burst water mains which impacted other infrastructure or society between 2009 and 2017 were summarised and geocoded (Fig. 2, Appendix A). The preparation of these data is described in more detail in the methods section.

2.3 Soil sand content maps

As the majority of water pipes are found at approximately 80 cm depth, maps of maximum soil sand content at 80 cm depth were produced for England and Wales by reclassifying the 1:250,000 scale National Soil Map and Land Information System (LandIS) data (Cranfield University, 2016). Soil texture (the composition of sand, silt and clay) varies with depth and across the national soil mapping units (which comprise numerous soil types). The maximum sand content within the soil mapping was chosen instead of the mean to highlight areas with even small areas of sandy soil, and to minimise the over-mapping of loamy soils which results when soil textures in regional soil textures are averaged.

3 Methods

The interactions between the four methods, their study areas and the data used is summarised in Figures 1 and 2.

3.1 Method 1: The impact of burst water mains on road surface quality

The impact of burst water mains on co-located roads was investigated across the county of Lincolnshire (Fig. 1) for which both road condition and water infrastructure data was available. Annual (2008-2013) Road Condition Index (RCI) SCANNER data was provided by highways engineers at the County Council. RCI is measured on a scale from 0 (good condition) to 315 (failed road) (Wallis, 2009; UK Roads Board, 2011; Pritchard et al, 2014b, 2015b). Roads with RCI >100 require maintenance.

The road quality before, and after, reported burst mains was compared. Each burst was buffered by 50 m to identify the surveyed road segments under the '*potential influence*' of the burst main (0-50 m, grey circles, Fig. 3), and an area which was presumed '*beyond influence*' of the burst (50-100 m, blue circles) but representative of similar soil and road materials. RCI change from before to after a burst was calculated and analysed against soil sand content at 80 cm depth.

Both degraded road conditions (positive RCI) or improved conditions (negative RCI) could indicate an impact from a burst main. As most road surfaces are in less than perfect condition, there are a number of scenarios in which a burst may impact the road surface quality, both positively and negatively. For example, an **improved road surface** may result when *a burst main significantly damages the road surface* leading to an extensive repair to a large part of the road, increasing the surface quality in this location. A **degraded road surface** may result when *a burst main does not damage the road surface, but does cause subsurface cavitation*. In this case, the road may be undermined (even a number of meters from the burst) which can lead to surface deformation. In addition, road cutting to access the pipe will likely lead to a decrease in surface quality. Finally, **little change in road surface** quality might be expected where *a burst main does not damage to road surface or cause* *subsurface cavitation.* Here the only change should come from the impact of digging and reinstating the road. The impact here is dependent on the quality of the workmanship.

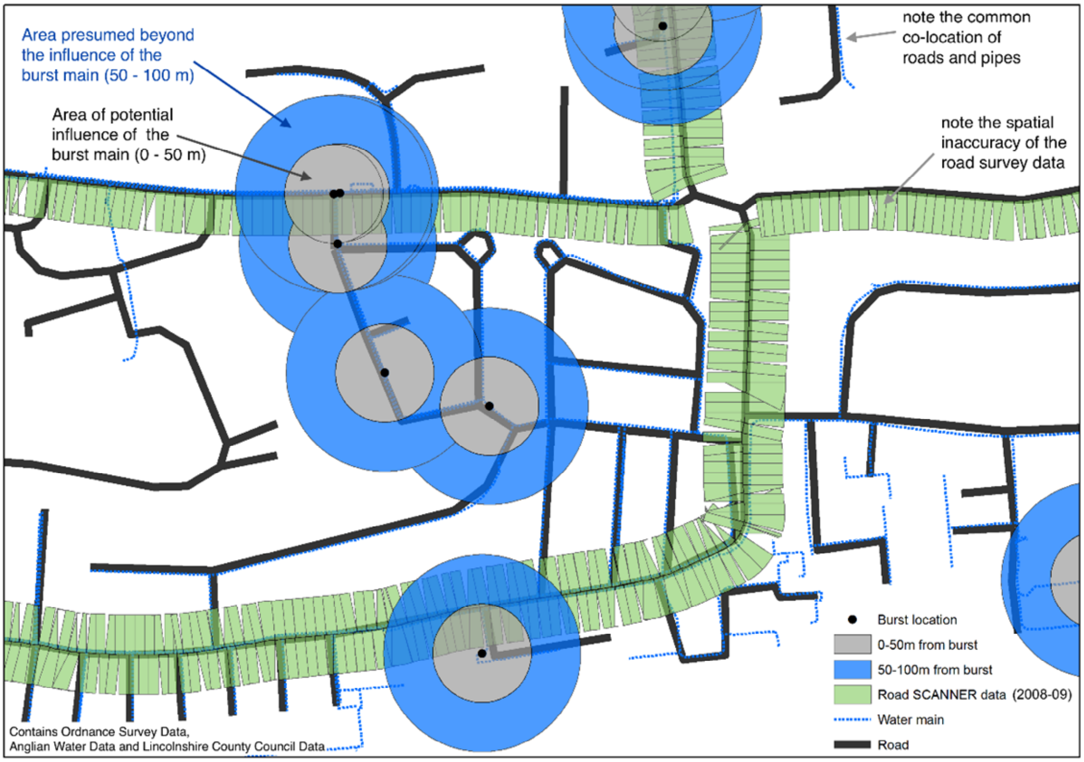

Figure 3 – Example region showing road sections which potentially have been influenced by a burst, and the similar road sections which are presumed beyond the area of influence (Method 1a). Burst data from the water company; Road data from the Local Council.

Road Condition (RCI) data was not available for all roads, in all years, and the opposite sides of the road were typically surveyed on alternate years (Fig. 3). The road condition survey area polygons are 10 m in length, but the GIS representation of these lengths (inaccurately) extend well beyond the road footprint (green polygons in Fig. 3). To minimise the impact of this spatial inaccuracy, a count (rather than the area) of these polygons was used, along with their RCI scores to calculate a change in condition between the survey dates before and after the burst.

3.2 Method 2: The impact of burst water mains on other water mains

It is generally not possible to determine the causality of a burst main from the location and date of burst. So, to gain indications if bursts in sandier soils were more likely to trigger subsequent proximal bursts, clusters of bursts were identified using expanding spatio-temporal windows: ((distances: 2, 5, 10, 30, 100 m) (times: 1, 5, 10, 100, 365 days)). These windows were chosen to identify the different failure patterns. For example, the smaller windows (e.g. 2 days, 5 m) may identify multiple bursts triggered directly by the bursts; through force transmission down the pipe, sand abrasion, or failures triggered by a common cause. Longer temporal windows may identify impacts stemming from secondary impacts, or chronic conditions. For instance, a road surface weakened from cutting to access the pipe, or due to voids, may increase differential traffic-loading forces on pipes, and so, increase the risk of failure. The number of burst clusters were compared with maximum soil sand content at 80 cm. The rate of failure of all bursts per km pipe, by sand content was also calculated. 50,901 bursts from Anglian Water between 2004 and 2015 were used in the analysis.

The rate of failure was calculated by dividing the number of bursts in clusters by the total number of bursts in each sand decile. By their nature, larger spatio-temporal windows have higher rates of clusters. Therefore, for comparison, the rates have been normalised by dividing the rate by the sum of all the rates, for each panel in the graph (Fig. 5). The calculation used is:

$$\text{Normalised rate} = (\text{clusters}_s / \text{bursts}_s) / (\Sigma_t (\text{clusters}_t / \text{bursts}_t) \quad [1]$$

Where:

clusters_s = the number of clustered bursts within a sand decile

bursts_s = the total number of bursts within a sand decile

clusters_t = the total number of clustered bursts in this spatio-temporal window

bursts_t = the total number of burst in this spatio-temporal window (the whole dataset)

3.3 Method 3: The impact of burst water mains on other infrastructure and society

A meta-analysis of over 30 UK local media reports between 2009-2017 was employed to identify the complex forms of failure arising from burst water mains. This time period was chosen for the widespread availability of UK web-based articles from this time. Google searches including key words such as "water main", "burst", "road", "electricity", "phone, "gas", and "sewer" provided articles. The date and impacts of the burst mains were recorded (summaries are provided in Appendix A). Burst location was estimated from the location descriptions in the articles, and were geocoded with www.gridreferencefinder.com. The geocoded data was imported into ArcGIS and attributed with soil sand content.

Spatial bias may (or may not) occur in the locations of the events, using this web-search approach. For example, if a particular newspaper has identified cascading failures in the past, it may be more likely that they may report these issues again. Conversely, if such failures happen weekly, these events may be under-reported as they are no longer "newsworthy". Future research should consider accuracy assessments of these approaches in more detail. In this scoping study, the assumption of no spatial bias has been made. The media articles are summarised in Appendix A.

3.4 Method 4: Cross-infrastructure workshop and 1:1 interviews

A single stakeholder workshop, involving representatives spanning water, electricity distribution, gas distribution and highways sectors was used to elicit the key impacts of burst water mains on other infrastructure. Workshop attendees were predominantly asset or performance managers or data-specialists in their infrastructure organisations, or infrastructure focussed academics. The workshop employed a trained facilitator and used a semi-structured experience-sharing discussion format. Preliminary discussions focussed on experiences of sand washout impacts on infrastructure assets, service provision and risk management challenges. After receiving experience sharing, initial results from early data analysis was shared with the workshop and feedback was received. Crucially, the workshop and interviews provided a framework for extracting infrastructure operators' perspectives on cross-infrastructure impacts of burst mains.

Detailed notes of the discussions were made as opposed to audio recordings because the experience of the authors has found that workshops can result in poor quality audio, which can be difficult to subsequently transcribe. Follow-up semi-structured one-to-one interviews with workshop participants further explored particular issues of interest. Interviews were also held with local authority, rail and telecom representatives who were unable to attend the workshop, and notes or audio recordings of the discussions were collected. Established analytical methods were employed to analyse the workshop notes and interview transcripts, with an interpretive approach, based on inductive insights from the data, used (Saldana, 2009). This involved the manual coding of the data, resulting in the inductive identification of key themes and sub-themes. Details from these discussions are illustratively incorporated in the results and discussions. For brevity, citations of comments from the workshops and interviews, and the meta-analysis media articles, are omitted from the discussion text.

4 Results

The results of the methods are briefly described below and in more depth in the Discussions. Where figures include error bars, they show the 95% confidence intervals for the Poisson mean. This interval is calculated by transforming a symmetric 95% confidence interval (CI) for the logarithm of the mean.

4.1 Method 1 Results: The impact of burst water mains on road surface quality

In East Anglia (Fig. 1), 93% of minor (B) roads have pipes within 16 m of the centre line of the road. Thus, it is logical that a failure in the pipe network will impact directly on the road, through direct damage, subsurface void formation, or indirectly through road-cutting to access and repair the pipe. To test this, the change in road condition (RCI) was assessed (prior to, and after a burst) using annual road condition surveys for 232,897 10 m road segments which were within 50 m of a burst main (*"potentially influenced*") and 262,140 segments which were between 50-100 m from the same bursts (deemed *"beyond influence"* of the burst) (Fig. 3).

The mean RCI change was approximately 0 (Fig. 4), with consistent interquartile range (IQR) for all roads, except those within 50 m of a burst main, and built on sandy (70-90%) soils. These showed greater spread in the change in road condition, which may indicate that greater remedial work is required to roads following a burst in sandy soils. Because of the large number of observations, the difference in the spread of the data is statistically significant. Even so, the difference in the spread is not very large, so while it does appear to support the scenarios of failure described in 3.1, caution should be applied to drawing strong conclusions from this analysis, in isolation.

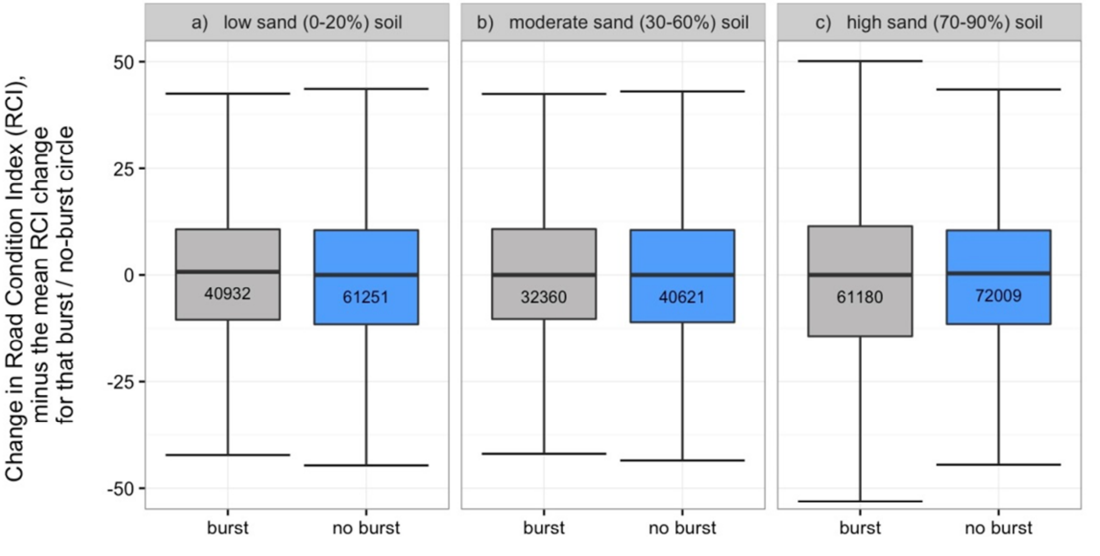

Figure 4 - Comparison of the change in RCI before and after a burst water main (minus the mean RCI change for the circular sample area (Fig. 3). The numbers on the box plots represent the number of analysed road segments. Whiskers: Range excluding outliers (IQR +/- 1.5*IQR).

4.2 Method 2 Results: The impact of burst water mains on other water mains

Using 50,901 burst water main records, the spatio-temporal windows identified clusters for between 1% (1 day, 2 m radius) and 45% (365, 100 m radius) of the bursts. While the smallest spatio-temporal window shows low rates of cascade failure on sandy soils (annotation "a", Fig. 5) the converse is true for the largest spatio-temporal window (annotation "b"). In addition, the high rate of bursts for low-sand soils is apparent (annotation "c"). This may be indicative of common cause failures associated with clay soils (e.g. high corrosivity or shrink-swell potential). These clusters in the low-sand content soils increase with expanding spatio-temporal windows, reflecting the larger number of bursts in these corrosive and movable soils. The bursts data used shows only independent repairs, so jobs to repair previous repairs which have failed prematurely are excluded.

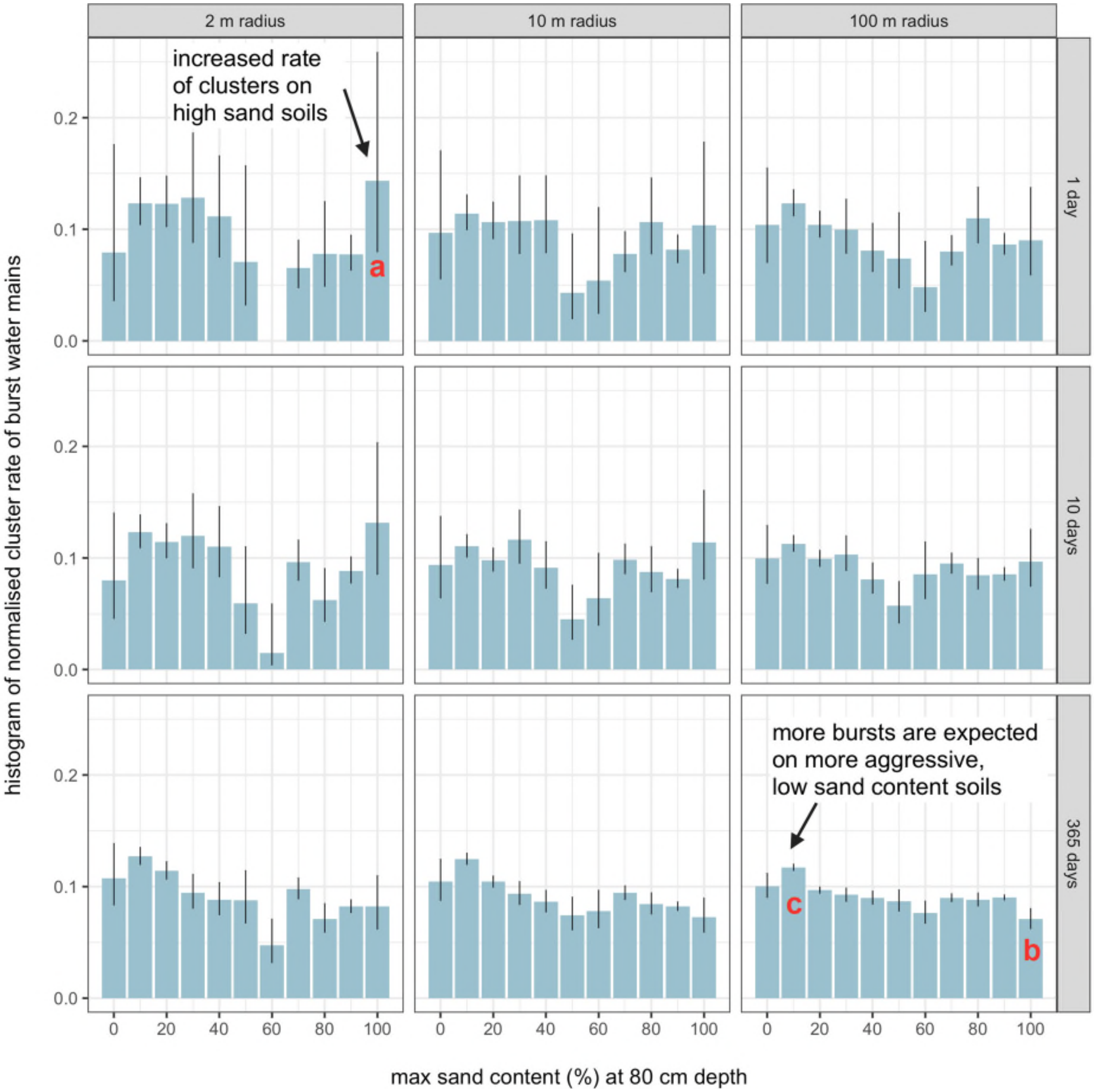

Figure 5 - normalised rate of (burst cluster) / (all bursts within expanding spatio-temporal window), by maximum soil sand content at 80 cm depth. Error bars: 95% CI for the Poisson mean. Higher bars indicate more clusters of bursts per initial trigger burst. For clarity, only 9 of the 25 spatio-temporal windows are shown).

4.3 Method 3 Results: The impact of burst water mains on other infrastructure and society

The meta-analysis of media reports identified 33 multi-infrastructure events across England and Wales between 2009 and 2017 (locations plotted in Fig. 2, and summarised in Appendix A). The articles provided detailed information on the impacts of burst mains on infrastructure and wider society (e.g. school and hospital closures, length of traffic delays, amount of bottled water delivered, and the emotions of those impacted by the events). The impacts of burst water mains on infrastructure and wider society are summarised in Fig. 6 and Table 1. Co-located roads and gas pipes were the most commonly affected infrastructure.

The overall rate of bursts is only slightly controlled by soil sand content. For example, the rate for the bands in Figure 7 ranges only from 0.97 – 1.05 bursts per km. However, the meta-analysis of the media reports indicated that sand content does play a controlling role in the likelihood that an initial burst will *go on* to impact on other infrastructure or wider society. A substantially higher rate of media-reported cascading infrastructure failures was observed in sandy soils (Fig. 7).

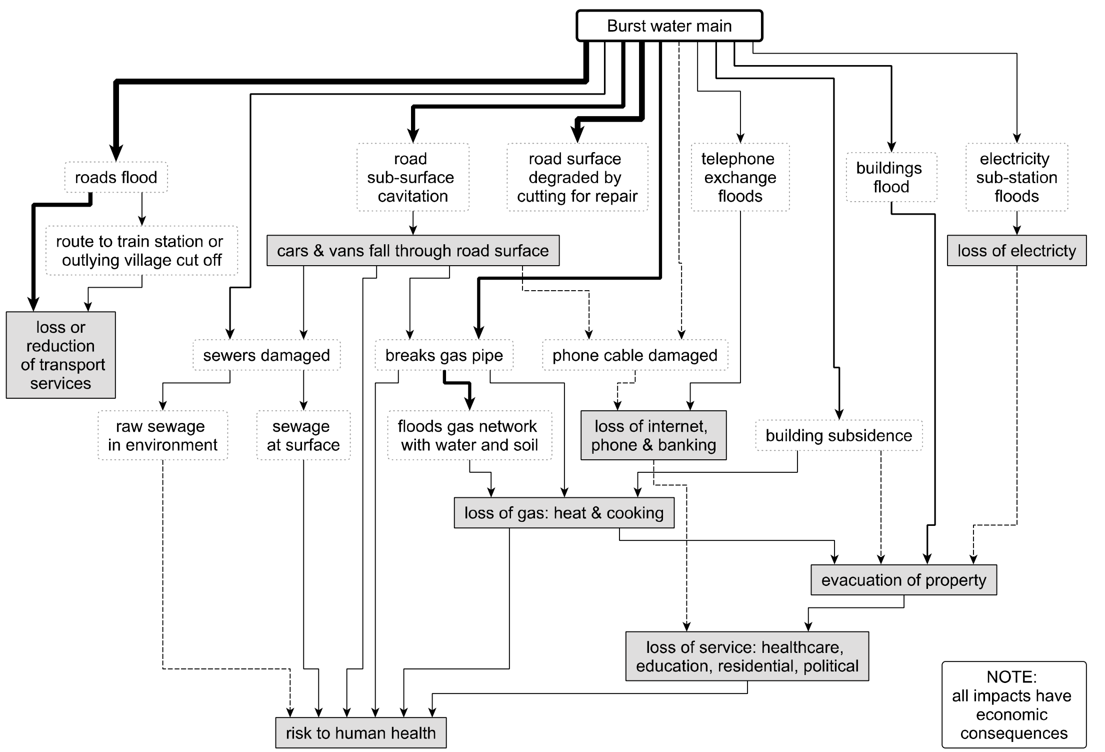

Figure 6 – Summary of impacts from burst water mains on other infrastructure and wider society. Schematic diagram based on analysis of 33 media reports, workshop discussions and interviews, showing impacts to other infrastructure and society. Line width represents the relative frequency of the impact.

Infrastructure	Reports	Impacts
Road	21	Flooding, surface damage, sinkholes (+/- vehicles in them), traffic delays, closure
Houses	10	Loss of water, loss of gas, flooding, sewage flooding, evacuation, subsidence, extensive cracking
Gas	8-11	Loss of gas, fractured pipe, flooded and sediment in gas mains
Buildings	6	Flooding of county hall, schools closed, hospital wards and accident and emergency (A+E) department closed and patients transferred. Shops closed. Lamp posts unstable.
Sewers	3	Blocked sewers leading to foul flooding. Pumping station filled with sand. Tankers required to pump sewage. Sewer collapse. Raw sewage in garden.
Health	3	Health suffering due to cold exposure, sewage in gardens, A+E closed, and patients moved. Toilets out of action.
Electric	2-5	Loss of electronic payments. Facilities unable to open.
Water	2-3	Loss of water, second pipe repair in close proximity.
Telecoms	2	Loss of phone and internet services (including no credit card payments at a supermarket for many hours.)

Table 1 - Summary of impacts on other infrastructure from burst water mains (from analysis of media reports). Where Reports indicate a range (e.g. 8-11), this is due to uncertainty in the descriptions provided by the article.

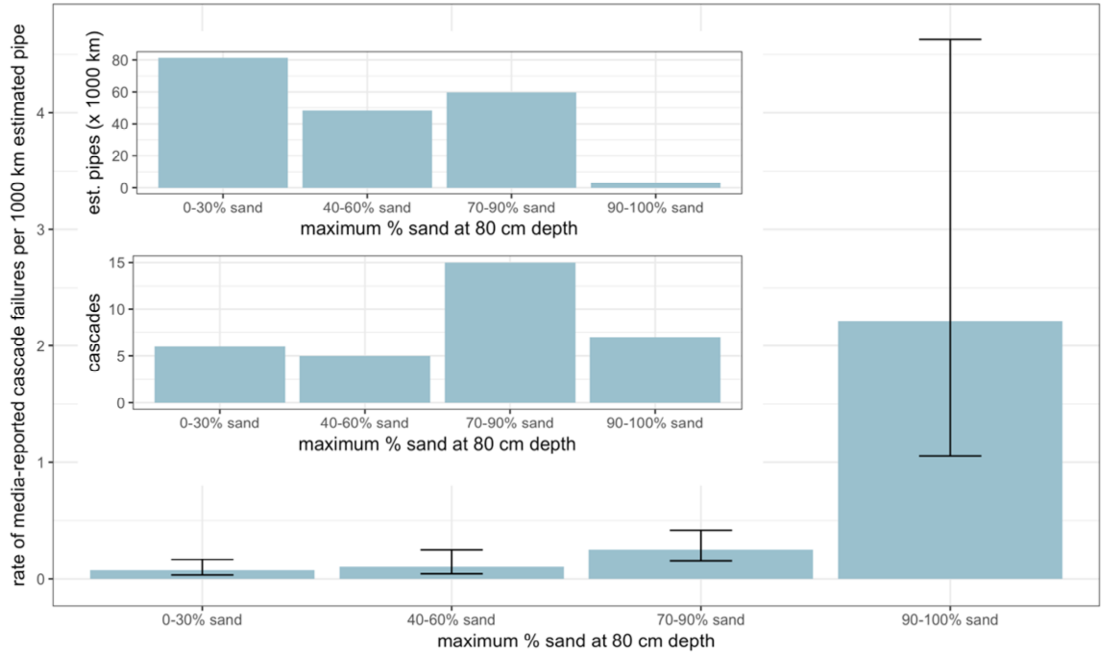

Figure 7 – Main figure: Rate of media-reported cascade failures, normalised by estimated pipe length in each soil type. Error bars (95% confidence interval for the Poisson mean). Top inset: Estimated pipe length across England and Wales, by sand content. Bottom inset: number of media-reported cascade failures, by sand content.

4.4 Method 4 Results: Cross-infrastructure workshop and 1:1 interviews

The workshop and interviews provided many detailed insights into the hidden costs and pressures arising from burst water mains. These impacts are also included in Fig. 6 and aspects are described in more depth in the Discussion section.

5 Discussion

This section combines discussions from all the methods. Method 1 explored the impact of burst on road surface quality, and Method 2 looked at the spatio-temporal clusters of bursts by sand content. Limitations in the quantity, consistency and spatio-temporal accuracy of other infrastructure failure datasets did not allow cluster analysis for other infrastructure types. Method 3's media meta-analysis and the workshop / interviews of Method 4 revealed insights into the wider impacts of water mains on other infrastructure that were hidden from Method 1's and 2's spatial data analysis of industry-reported failures. The media articles provided in depth details on the wider impacts on society (families, schools, businesses etc.), albeit in a more sensational and qualitative manner than other reporting methods. The workshop and interviews provided the behind-the-scenes views from infrastructure operators on how large failure events impact service delivery and repair processes. In the workshop, network operators described cross-infrastructure failures as low frequency, but moderately high impact events. The importance, and difficulty, of cross-infrastructure communication and co-working was identified (Dawson et al., 2016) the value of cross-sector regional task groups was asserted and many impacts on other infrastructure networks were discussed. Below, highlights of some of the common impacts on key UK infrastructure types from burst water mains are provided. This is followed by a discussion on the impact of burst mains on wider society and the implications of this work for risk management. Finally, a brief discussion of the performance of the mixed methods approach is provided.

5.1 Roads

Flooding and damage to roads are common direct impacts from co-located pipes (Table 1, Appendix A). Void formation under the road surface can also impact on safety (e.g. vehicles falling through the road surface into voids). Minor and local roads are more likely to be impacted by water mains failures than major roads, as minor roads are more commonly underlain by water pipes and have a level of engineering reflective to the lower levels of traffic. However, examples where major roads have been impacted include a burst-formed void under a road in Kent costing a water company £640,000 in remediation, and causing a 25 day road closure. Burst mains have also flooded motorways causing significant disruptions.

Bursts in sandy soils appear to be slightly more likely to change the road surface condition than bursts in other soil types (Fig. 6). Even if the road is not damaged by the burst and water pressure, pipe repairs commonly require cutting the road surface to access the failed pipe. Highways authorities within England and Wales report that such cutting and trenching impacts the structural integrity of the road, and potentially reduces the roads service life by 30% (Asphalt Industry Alliance, 2016). This was also reported independently at the workshop and in the interviews. Cuts to the road surface represent physical lines of weaknesses in a previously solid, load bearing surface, as well as the subsurface. Cuts and trenches are well known to lead to subsequent pot holes or surface deformation features, including differential settlement. It was reported by highways engineers that cut roads not only have a shorter serviceable life, with higher maintenance costs, but also that cuts may be contributory factors to subsequent water pipe failures at the same location.

Where cavitation occurs over an extended period of time (due to a small water leak from mains, or frequent infiltration / exfiltration of sewers), a commonly reported symptom is road profile change, which can provide an early warning of issues beneath the road. Multiple media reports described how small road surface deformations were initially misdiagnosed and treated as simple surface failures, only for a larger deformation or hole to appear the next day.

5.2 Ports and railways

Ports and railway stations represent critical access nodes for international and national transport. The vulnerability of the access routes to the Ports of Felixstowe and Lowestoft were discussed in the workshop, as parts of these key transport routes are on sandy soil. If access roads are closed due to cavitation from a burst main (or tidal surge, as occurred outside the Lowestoft train station in 2014) then access to the ports / railway would be severely restricted. The economic and transport consequences of port closures are severe. As well as preventing access to these transport nodes, burst mains can also affect railway infrastructure itself. In August 2016, a burst water main contributed to the collapse of a railway embankment and bridge in Leicestershire disrupting rail journeys for thousands of passengers for a number of days.

5.3 Gas distribution pipes

Gas pipes can be damaged by water mains as a result of 1) the pressure of the water itself, 2) water + soil mixed to an abrasive “sandblasting” slurry, or indirectly through 3) cavitation and subsequent damage by vehicles or road surface collapse. Such failures commonly cause many hundreds of houses to lose gas supply (Appendix A).

The cost of repairs to gas pipes is reported to be insignificant compared to the cost of removing water and sediment from gas pipes. In some reported cases, up to 10,000 litres of water and debris needed to be pumped from the gas network. Removing water and sediment is a complex process leaving properties without gas for extended periods of time. In one burst-triggered gas network failure, supplies to 250 customers were lost for 7 days due to the valve-less low pressure gas networks. These pipes required repeated digging (each time damaging the road) to 1) insert a camera to find the blockages, 2) to isolate the main, and then 3) to physically isolate each property. There are additional regulator-imposed charges associated with loss of service and potential health risks for vulnerable people due to lack of heating.

Workshop discussions also highlighted that health risks are higher when, following a leak, gas enters a building. This most often occurs through migration of gas through the soil into houses, but also can occur when water enters a damaged gas main. As more water enters the pipe, the gas pressure will drop for short periods to a point where some pilot lights on domestic boilers can extinguish, leaving gas entering into unlit boilers. These types of failures are reported to be hard to predict. Gas meters and boiler valves can also be damaged by water and debris in the network which bears additional repair costs.

5.4 Buildings and houses

Public and private buildings are commonly impacted by water mains failures, both directly (e.g. flooding or subsidence) and indirectly through loss of services. In one burst near Bristol, 8,000 homes lost water supply for 3 days (Appendix A; ref 2). Properties can also lose gas supply, or expose residents to risks. In one example, 25 homes were evacuated due to a large gas leak. When sewers are blocked due to sediment ingress, sewage can enter houses through the toilets. Property subsidence has also been reported following a burst main near a house on sandy soil as a result of cavitation. This led to cracks opening up in the walls in the winter, and health impacts for the vulnerable residents were reported.

5.5 Other water mains

While multiple water mains failures were only specifically reported 3 times in the media analysis, the GIS cluster analysis identified that 2-3% of bursts were co-located with another burst within 5 metres and 5 days of the original burst. For clusters within 2 metres and 1 day, a slightly higher rate of failure was observed for pipes in the sandiest soils (Fig. 5, annotation “a”). A water company reported higher rates of multiple pipe failure due to sand abrasion for softer polyethylene pipes than metallic pipes. Subsequent research could repeat this method by looking at each pipe material (e.g. cast iron, asbestos cement, PVC, polyethylene) in isolation to highlight the risk of sand abrasion on the different pipe materials.

5.6 Sewers

Sewer impacts from burst mains include physical damage to the sewer, leading to blockages and flooding by sewage of roads and gardens. Such incidents are unpleasant and carry associated health risks. When properties lose sewerage, tankers are required. As sewers do not require the same structural integrity as gas and water mains and have joints every few metres, they are vulnerable to exfiltration of sewage and infiltration of water and particles. The change between high and low external pressures can lead to void formation around the sewer. Increased water pressures can come from burst mains, natural events such as storm surges, or high rainfall events. Due to their non-cohesive texture, sandy soils are more likely to be washed into the sewers than clays and loams.

A water company that manages both water distribution and sewerage networks reported that voids in sandy soils around sewers are more problematic than around mains pipes. When reported, voids can be filled with a resin. If left unchecked, the structural integrity and flow pathways of the sewer can suffer as the sewers settle into the void. This in turn can increase the probability of a subsequent blockage, which can in turn lead to sewer flooding.

5.7 Electrical distribution

Flooding from burst mains is a potential risk to urban electricity infrastructure, where substations and electrical equipment are commonly located in basements or underground recesses. One below-ground substation was reported to have suffered two floods in two years resulting in £1m costs and subsequent relocation of equipment. Any disruption to electricity supply can have wide impacts, including to IT networks.

Impacts on electricity distribution networks from sand-washout events were less frequently identified, with 12% of media reports mentioning electricity distribution impacts. An electrical Distribution Network Operator attributed this low impact rate to buried electricity cables having sufficient flexibility to accommodate a loss of ground support and that the higher voltage cables were buried at greater depth. However it was reported that older forms of lead-paper insulated cables exhibit limited flexibility and are thus more vulnerable. Another reason for the resilience of the electricity networks is that they are reconfigurable, with supplies rarely interrupted for more than a few seconds, anywhere other than single source nodes of the network.

Electric cables are most commonly damaged by “third party strikes” when water companies and gas companies dig down to repair or replace their assets. Notable advances have been made by utilities to avoid these strikes and the associated risk to human life, and additional damage, but they still do occur as the electric cables often sit on top of water mains.

5.8 Telecom cables

Telephone cables appear resilient to burst main impacts, possibly due to the prevalence of overhead lines in older residential areas (so co-location is not an issue). Only one example of a burst main resulting in telephone disruption was categorically identified by the media analysis. However, in this instance, when the phone lines were cut off, a very large supermarket was prevented from accepting credit card payments until the lines were repaired.

5.9 The impacts of burst water mains on wider society

The socio-economic implications of burst mains range from simple repairs of the infrastructure to more complex impacts such as increased travel times, loss of work, and disruption to businesses through loss of footfall or disruptions to electronic payments. If roads serving isolated communities are closed, the impact of even a week of lost earnings can be catastrophic for small businesses. Schools and hospitals (and many businesses) cannot open without water, and numerous examples of such closures were identified. When schools close, there is a subsequent impact on the local economy as many parents cannot attend work that day.

Whilst health is rarely affected directly by burst mains, secondary impacts were identified. Examples include closure of hospital units and the movement of vulnerable patients to other hospitals, raw sewage in gardens and subsidence leading to the formation of cracks in houses with associated heat loss and implications for the health of older residents. When gas mains are ruptured, houses may be evacuated to minimise health impacts. When cars become trapped in holes in the road there is potential for significant injury or death. While it is the duty of infrastructure operators to minimise risk, there are also longer term socio-economic and liability costs if human health is affected. Furthermore, any major disruption to infrastructure service provision can result in public relations and customer satisfaction impacts.

Road damage or flooding can extend travel times and distances and can result in reputational damage to the water and highway operators. Diversions in rural areas of up to 48 km were identified in the media analysis. Major voids will lead to longer road closures, and greater socio-economic impacts.

5.10 Implications of this research for risk management

Sand washout is not the most common, or damaging, soil related geohazard (Pritchard et al 2014a). However, due to the distribution of sandy soils (Fig. 1), regional trends can be observed. While some local authorities (particularly those in sandy soil areas) have dedicated teams to address this issue, most utilities only deal with these events on a case-by-case, reactive, basis. Although some of the impacts of these events have been considerable, it was noted by infrastructure operators that their low-frequency make them difficult to consider as part of many asset management plans.

Monitoring of infrastructure stability can incur substantial costs and is often unfeasible across an entire network, so reactive responses to infrastructure failures are common. Nevertheless, it was noted that the use of soil maps and other geohazard datasets to identify assets and communities at risk from washout and other events would be a first step most infrastructure organisations could take to identify (and then potentially mitigate) their exposure to these risks. Such maps can inform decision-making, help prioritise areas for increased levels of maintenance, or faster response times and to inform asset management plans.

The infrastructure-provided failure data analysed did not provide the severity or scale of the impact. One burst main may cost a nominal amount to repair, but one which impacts on other infrastructure systems can have significant costs associated. Each burst, irrespective of its impact, is currently represented by one record each in the company bursts database. Utilities may wish to record the severity and scale / cost of the impact in their relational spatial databases to identify areas of their network which commonly are more expensive to fix. The importance of collecting and maintaining highly accurate spatial data for assets and failures is asserted, if later data-analysis is to be undertaken and meaningful results provided to inform future decision making.

Information sharing around infrastructure interdependencies between utilities is often only undertaken on a 'need to know' basis. This is particularly true where issues of commercial confidentiality and / or national security apply, for example to national critical infrastructure. Because of a focused remit on their own infrastructure, low levels of information sharing on environmental hazards and risks occurs even between similar networks in the same geographic region. However, many countries are seeing a transition towards large parent companies owning multiple utility companies (e.g. in the UK Cheung Kong Infrastructure Holdings Limited largely owns Northern Gas Networks, Northumbrian Water and UK Power Networks, and also owns a strategic stake in the Southern Water Group.) As a result, where appropriate, information sharing between these companies operating in the same area is encouraged by the parent company. Independent operators working in similar regions may take part in local infrastructure groups, or national infrastructure resilience networks.

Many utilities stated that their awareness of systemic vulnerabilities, risks and interdependencies was less than ideal, and expressed their desire to better understand the societal risks beyond that of their own network concerns and liabilities. A desire for greater quantification of the impacts of these type of low frequency events on levels of service and resilience was expressed, as the predominant focus is on the reduction of high likelihood, high impact risks. While this research begins to address these desires, there is potential for a more thorough analysis of these types of failures, using and building on the approaches used in this research. UK wide data on water mains bursts is being collected in the National Failures Database, held by the UK Water Industry Research Organisation. Similar databases for other infrastructure communities would be of value. The consideration of lower likelihood, moderate impact risks is being encouraged by the UK water regulator OFWAT in their Resilience in the Round documentation (OFWAT, 2017)

5.11 Assessments of the mixed-methods approach

This scoping study sought to describe and begin to quantify the impacts of burst mains on other infrastructure and society. A mixed methods approach, rather than a pure GIS data analysis of reported infrastructure faults and failures was used, and the value of the details provided by the meta-analysis of media reports and expert knowledge distilled from workshops and interviews quickly became apparent.

The spatial data analysis quantified the control of soil on the impacts of burst mains on road surface quality (Method 1), and on the likelihood of subsequent bursts (Method 2). However, the unavailability and/or inaccuracy of many infrastructure datasets did not permit the desired identification of many cascading infrastructure failures in this approach. While data is now being collected on the duration and number of properties impacted by water supply interruptions, the industry-reported burst data used in this research data did not describe wider societal impacts, nor the scale or cost of the failures. The industry GIS data was usually restricted to the location, date, and repair type undertaken. In contrast, the meta-analysis of media reports (Method 3, impacts summarised in Appendix A) provided qualitative descriptions of both infrastructure failures and the impacts on health, economy and people. Because media reports tend to focus on the larger bursts, the impacts are not representative of all bursts. However, analysis of these reports identified that the rate of these dramatic failures per 1,000 km pipes is higher in areas of sandy soils (Fig. 4). Because of the depth of information gleaned from this approach, media meta-analysis is encouraged for other studies of low frequency, moderate impact local environmental risks. Further work on the removal of any spatial bias from such reporting is recommended. Social media feeds may also serve as a crowd sourced dataset for identifying these types of failure. The workshop and one-to-one interviews with infrastructure owners and operators (Method 4), captured detailed perspectives on these cascading infrastructure failures and their impact on service delivery, costs, responses and management plans. The combination of these methods led to more quantifiable, descriptive and useful results than would have been possible if each method was used in isolation.

6 Conclusions

Diverse examples of the cross-infrastructure impacts from burst water mains have been identified and discussed. Cascading infrastructure failures, while occurring in many soil types, appear to be more than three times as common in soils with high sand content (Fig. 7). While the investigations undertaken in this research have focussed on areas within the UK, the same principles will apply in any country where sandy soils are present (e.g. Majid et al., 2007). The types of failures described tended to be low frequency, moderate impact events. Due to asset co-location, roads and gas pipes are the infrastructures most commonly affected by burst water mains (Fig. 6). There are substantial direct and indirect economic costs of these events.

The impact of burst water mains on other infrastructure can be long-lasting (e.g. reduction in the structural integrity of a road) or costly to repair (e.g. removing water and sediment from a flooded gas network). Burst mains can also impact on the wider society; disrupting healthcare, increasing travel times, or closing local businesses, government operations and schools. The costs of these societal impacts are rarely quantified and are typically borne by affected individuals. Wider discussions around cascading failures are of relevance to regional infrastructure and resilience groups.

The research illustrates the potential value of mixed methods approaches to investigate such complex infrastructure hazards and risks. The geospatial data analysis of infrastructure failures provided insufficient information to fully address questions about the impact of burst mains on proximal infrastructure and society. In contrast, the meta-analysis of local news stories provided rich information relating on the cascading impacts of burst water mains. Furthermore, the direct input from infrastructure operators through the workshop and interviews obtained valuable information on their views on these risks to their infrastructure resilience. Thus, the authors believe that mixed methods approaches holds great potential for infrastructure research, but such approaches do require careful development and evaluation. To benefit more from these approaches, infrastructure operators are encouraged to improve the spatio-temporal accuracy of their failure / condition mapping, and the speed to which the data on these failures are made available throughout the company.

Marker (1998) argued that earth science is generally underused in spatial planning. Twenty years later, the comment can be re-stated. Soil maps, similar to those used in this research can help infrastructure companies identify assets in soils vulnerable to sand washout, and other more common soil-related geohazards (Pritchard et al 2014a). Clear identification of the hazards present in a local area will enable informed decision making. Vulnerable assets can be identified, assessed and repaired or proactively replaced to minimise cascading impacts.

Author contribution. Farewell and Jude conceived the study. All authors were involved in data collection including the workshop, with Farewell and Jude analysing the results. All authors contributed to the manuscript.

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Photo gallery: Burst water pipe floods road in Dersingham: http://www.edp24.co.uk/news/environment/photo_gallery_burst_water_pipe_floods_road_in_dersingham_1_3851694, last access: 17/03/2017

Burst water main leaves gaping hole in A320: http://www.getsurrey.co.uk/news/local-news/burst-water-main-leaves-gaping-4813168, last access: 17/03/2017

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Read more at http://www.stokesentinel.co.uk/2ft-sinkhole-fenton-road-caused-burst-water-pipe/story-21070606-detail/story.html#dGI419Owhiv25MTP.99: http://www.stokesentinel.co.uk/2ft-sinkhole-Fenton-road-caused-burst-water-pipe/story-21070606-detail/story.html, last access: 20/03/2017"

A272 closed at Buxted: http://www.sussexexpress.co.uk/news/county-news/a272-closed-at-buxted-1-6557919, last access: 20/03/2017

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Woking loses water supply due to burst pipe: http://www.getsurrey.co.uk/news/surrey-news/woking-loses-water-supply-due-6941235, last access: 21/03/2017

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Appendix A

ID	Date	Sand %	Summary of Media Report	URL
1	23/02/2009	93	15 cm PVC main burst. Damaging road surface. Police involved. 69 houses off water. Fire engine called to pump water. Bottle water. Took 20 hours to fix pipe.	http://www.northnorfolknews.co.uk/news/cromer_water_main_fixed_1_533520
2	02/11/2009	80	Large diameter main (76 cm) burst. 8000 homes without water. 18 schools closed. Bristol Water and Red Cross handing out water. 19 people rescued by dinghy, and spent the night in a church hall. Huge hole in road. Gardens destroyed.	http://www.bbc.co.uk/news/uk-england-bristol-29373980
3	06/10/2011	95	Burst main floods gas pipe. 650 houses off gas. 80,000 L of water removed from gas network. Significant damage to gas meters and appliances. Gas company supplied electric hobs and heaters to affected homes. Set up a customer centre at the local church.	http://www.bbc.co.uk/news/uk-england-dorset-29362291
4	27/09/2012	95	Gas network flooded with water. 400 homes affected, some for more than 2 days. Engineers required to carry out safety checks, and reconnect gas. Customers off gas for 24+ hours are financially compensated.	http://www.bbc.co.uk/news/uk-england-dorset-29929187
5	10/10/2012	87	Burst water main. Major incident declared at Scunthorpe Hospital. No drinking water & toilet flushing affected. Patients told not to attend A+E if possible.	http://www.itv.com/news/calendar/update/2014-10-05/water-supplies-restored-to-hospital-in-lincolnshire
6	20/12/2012	47	A main road and footpath in Lincoln are closed for two days after a burst water main.	http://news.bbc.co.uk/1/hi/england/lincolnshire/8337851.stm

7	06/04 /2013	23	Burst main - car fell through road. Closed road leading to gridlock. 100 m of road to be reinstated. 30 cm main. Road closed for 3-4 days. Water supplies off.	http://www.getsurrey.co.uk/news/local-news/burst-water-main-leaves-gaping-4813168
8	26/04 /2013	11	Burst main leads to void under road. Car becomes stuck in hole. Both lanes closed. Many roads in Walton gridlocked. Police called to scene. Council made aware.	http://www.getsurrey.co.uk/news/surrey-news/car-trapped-sinkhole-opens-walton-7936966
9	01/11 /2013	92	1.2 m x 1.2 m void under road. Not sure if it is caused by gas leak, or if the void caused the gas leak. Road closed for a number of days. Smelling gas for a month before the hole was discovered.	http://www.getsurrey.co.uk/news/surrey-news/road-closure-after-sinkhole-appears-7259207
10	06/01 /2014	87	Car stuck in hole on A320. No disruption to water supply. Water company paying car insurance claim. Resurfacing road. Road closed for 1 days. Police closed road. 15 inch main.	http://www.getsurrey.co.uk/news/surrey-news/car-becomes-lodged-burst-water-6983196
11	16/01 /2014	87	Ground collapsed under car, driver missed work. Lamp post unstable, electric supply isolated. Water supplies to area affected. Schools in Chertsey and Woking closed. Centre for disabled kids and adults closed. Extensive damage to roundabout, 3-4 day closure. 38 cm main.	http://www.getsurrey.co.uk/news/local-news/video-ground-just-collapsed-under-4809243
12	21/03 /2014	95	Burst main. Closed road to facilitate repairs. Also damaged electricity duct. Found second water leak. Interim repair first, and full repair in a few weeks.	http://www.worcesternews.co.uk/news/10120224.Road_is_reopened_after_leak_in_pipes/

13	09/04/2014	95	100-year-old large burst main- 1000's people off water. Significant road damage (A6). Road closed for more than a week. Busy commuter route near M1.	http://www.bbc.co.uk/news/uk-england-leicestershire-25619109
14	13/04/2014	64	Old mine tunnel collapse which also damaged sewer pipes. The main impact here is the economic impact on local businesses. One road closure has lost a butcher 20% of his business, and a fish and chip shop has had no passing trade. The road will take more than a week to repair.	http://www.bbc.co.uk/news/uk-england-cornwall-25975404
15	17/04/2014	95	Another car in A320 hole. 38 cm Victorian main. Local traffic congestion. PR issues now because of repeated problems with cars falling through roads.	http://www.getsurrey.co.uk/news/surrey-news/affinity-water-continue-patchwork-repairs-7000547
16	22/08/2014	39	Burst water main. Void formation - driveway collapse and household subsidence. Cold air coming through cracks, with claimed health impacts. Insurance loss adjustors and legal representatives will be agreeing the next steps.	http://www.worcesternews.co.uk/news/10354380.We_re_scared_our_houses_are_collapsing/
17	26/09/2014	23	Burst main closes main road in Swindon for many days. 30 m of road surface damaged by main burst (30 cm).	http://www.bbc.co.uk/news/uk-england-wiltshire-22312127
18	28/09/2014	95	Burst main (caused by BT contractors). Floods 90 homes, 9 flats and retirement homes. Fire crews involved - bottled water supplied. 30 gas company staff involved. Gas supplies cut to 86 homes, removed 10,000 L of water from the gas network. Lots of sand in pipes too - complex engineering process to vacuum out the pipes. Giving out heating equipment.	http://www.getsurrey.co.uk/news/local-news/river-running-down-road-burst-6263464

19	30/09/2014	0	Mains bursts. Floods roads. Blocks sewers. Debris washing towards main road roundabout. Gas leak. Fire crew and local council workers both involved to unblocked sewers. Police closed road. 100s homes off water.	http://www.mynewtown.co.uk/viewerheadline/ArticleId/8437
20	04/10/2014	87	Burst main breaks gas pipes and flooded gas network. 755 properties with no heating or hot water for days. 100,000 L of water removed so far. 150 properties off gas for extended period. Distributing fan heater and warming plates. Working with local authority social services. Washing facilities for people provided by sports centres.	http://www.walesonline.co.uk/news/local-news/gas-disruption-nantyglo-leaves-hundreds-7660937
21	14/10/2014	88	Burst pipe. Floods 5 homes. Cut electricity supply and telephone lines. Bad PR for Yorkshire Water.	http://www.thetelegraphandargus.co.uk/news/local/airelocal/11757812.Residents_face_flood_after_pipe_gives_out/
22	04/11/2014	11	5 x 3.5 X 1 m deep sinkhole in garden from burst main. Destroyed pavement and garden. Began as a small hole in kerb. County council called, but no one came so police called. Police put up barriers. The next day, huge hole full of water. Anglian Water fixed the pipe when called.	http://www.northantstelegraph.co.uk/news/top-stories/sinkhole-opens-up-at-bottom-of-cottingham-garden-1-6509161
23	18/11/2014	87	Taxi stuck in 1.5 m wide pothole caused by burst water main in Hampstead. Road affected for a number of days.	http://www.hamhigh.co.uk/news/environment/taxi_stuck_in_pothole_caused_by_burst_water_main_in_hampstead_1_3946614
24	28/11/2014	93	Road closed for 3 days after burst cause road to collapse. Tree has fallen into hole. 10 houses off water for 6 hours, but took much longer to fix the pipe, as the actual leak was > 1 km away from the damaged road. Diversions in place.	http://www.kentonline.co.uk/sevenoaks/news/road-collapse-leads-to-closure-30803/

25	09/01/2015	0	60 cm hole in road. Caused by burst main / or "drainage pipe". Old mines also present in the area.	http://www.stokesentinel.co.uk/2ft-sinkhole-Fenton-road-caused-burst-water-pipe/story-21070606-detail/story.html
26	26/01/2015	76	1.8 x 2.7 m wide, 1.8 m deep void. Destroyed road. Gardens flooded with sewage. Cascading failure damages proximal water mains (more bursts) and sewers (damage). Sewage pumping stations no longer working as sand and gravel in the pumps. Exposes gas pipes - . Tankers pumping sewers "day and night". 35 properties affected.	http://www.kentonline.co.uk/romney-marsh/news/huge-sinkhole-opens-near-homes-27226/
27	27/01/2015	72	Burst main fixed rapidly, but road remains closed to allow tarmac to set. Buses running 60 minutes late.	http://www.bournemouthecho.co.uk/news/11633506.Burst_water_main_repaired_but_traffic_misery_continues_for_motorists_in_Branksome/?ref=mr
28	29/01/2015	40	Burst main closes road. Water coming out of BT manhole. Water flowed onto carriageway & freezes. Traffic backed up 3 km. Gridlock on surrounding roads. 1 primary school closed.	http://www.sussexexpress.co.uk/news/county-news/a272-closed-at-buxted-1-6557919
29	03/02/2015	67	Burst main floods allotments. Complex fix as gas pipes and power cables close to water main. 15 cm main. Some properties off water. Bottled water provided.	http://www.ilfordrecorder.co.uk/news/environment/burst_pipe_in_woodford_green_leaves_residents_without_water_and_an_allotment_flooded_1_3930119

30	04/02/2015	89	Burst main floods gas network. 297 houses off gas. 200 homes off water. Heaters and portable cookers provided.	http://www.examiner.co.uk/news/west-yorkshire-news/hundreds-homes-moldgreen-dalton-tandem-7855557
31	06/02/2015	86	Burst main - sandy torrent of water, flooded 3 homes, turned road into "sodden beach". Water up to knee height - water up to 1 m high in houses. No water. No power. Road blocked for repair by police, fire crews required to pump water. 15 cm main.	http://www.edp24.co.uk/news/environment/photo_gallery_burst_water_pipe_floods_road_in_dersingham_1_3851694
32	08/05/2015	40	Burst main forms a void under road into which a Severn Trent van falls, cracking a gas pipe leading to the evacuation of 25 homes. Tens of thousands of pounds of flood damage. Roads closed for many days. Local council records flooded and offices closed for many days.	http://www.bbc.co.uk/news/uk-england-derbyshire-22050687
33	19/11/2015	100	38 cm main burst. Traders, charities and community centres closed, especially those with toilets, and cafes. Delays to repair of water supply because of a large electronic sign in a concrete plinth with a power cable rising through the middle, requiring specialist teams. Requested residents not to use dishwasher or washing machines to preserve water in tanks.	http://www.getsurrey.co.uk/news/surrey-news/woking-loses-water-supply-due-6941235
34	31/01/2014	39	Burst main. Flooding driveways and gardens. Traffic delays	http://www.getsurrey.co.uk/news/surrey-news/gardens-drives-flooded-after-a320-6860355