

Response to Reviewers

T. Acland

Thank you for your encouraging comments and helpful suggestions. We have taken them on board when revising the manuscript.

In response to your specific points:

1. Page 5 Sect 2 Line 10. The sewer data is explained as being of insufficient accuracy. It is also likely that these repairs were detected and resolved much later in time from the initial event. There are lengths of sewer still in operation although in poor condition, and stay that way for a long time.

Noted. We have mentioned this in our manuscript.

2. Page 7 Sect 2 line 20. Total mains length will include 'sundries' e.g. hydrant and wash out 'legs', short pipe section associated with valve complexes. The 7% difference in length may be greatly reduced by discounting mains less than something between 1 - 5m in length. You will probably end up spot on!

As previously discussed, this will likely be considered and revisited in a future publication. Thank you. For now we have included your comments in our discussion in this section.

3. Page 12 Sect 3 Line 20 and Page 13 Line 6. Are there proportionately more clamp burst repairs in the sand clusters than cut repairs? Cut repairs are usually more serious repairs and are more likely to be responded to quicker as an emergency. Clamp repair bursts may have been running for a much longer time and cause more sub-surface damage.

We did not analyse the cut/clamp data as many of the bursts data were missing this information, but will consider doing so for a future publication if the data becomes more robust. The alternative, as discussed later in the paper is to consider the impact on individual pipe materials.

4. Page 14 Sect 3.2.5. This is interesting. The development of wide tolerance repair fittings and the Regulatory/Customer service need for rapid supply restoration may be leading to water companies to repair rather than replace short sections of mains. We have definitions for sewer criticality but no national guidelines for water main criticality. Further there is no nationally agreed sharing of these details between the utility companies.

Noted. Thank you.

5. Page 17 Sect 3.3 Line 6. Whilst most hospitals have second/alternative supplies another significant issue is the closure of schools. The impact on students and families will be significant.

Yes indeed. We have noted this in our personal lives as well, and found examples of this in the media analysis and have mentioned this in the revised paper.

6. Page 11 Sect 3 Line 5. May be say that minor roads have a more historical or appropriate level of engineering instead of saying they are less well engineered.

We have revised our terminology to say that they have a level of engineering reflecting the lower level of traffic use.

Many thanks,

Tim Farewell, Simon Jude, Oliver Pritchard

K. Mertens

Thank you for the thoughtful and thorough comments and suggestions you have made. We have revised the manuscript following your general and specific comments.

General Comments:

Main comments General framing: The manuscript is currently presented as a scoping study which has two, very distinct hypotheses which require very different methodologies. On the one hand it is said that the authors want to investigate the relation between soil texture (sand) and the frequency of cross-infrastructure failure. On the other hand they want to test and evaluate a mixed methods approach for this kind of studies. I think these two objectives are too different to fit into one research paper, and certainly so if this research paper does only present the result of a scoping study. The current analysis does not test the second hypothesis. I therefore suggest dropping this second hypothesis and just mention that the purpose is to investigate the influence of soil on the consequences for society by combining different methods. Doing so the manuscript illustrates the value of mixed methods approaches, but does not test a hypothesis as to whether a mixed method is better or worse than another approach. It still allows you to discuss the merits of such an approach in the discussion and conclusion of your research paper. Alternatively, the objective could be to investigate the value of a mixed method approach to study this kind of things. The technical analysis of the correlation with soil can then be presented as one of the different methods or as a case study. It would be good if the objectives and research questions were made explicit. Now, I did only find the hypotheses and had to deduce the objective of the manuscript from it myself.

We agree with your comment about testing two hypotheses, so, as you suggest we have revised the manuscript to focus on the core objective of investigating how different soils influence the impact of burst water on society.

We have made the objectives / research questions explicit in the manuscript.

Page 3, line 15: How is this hypothesis tested? By presenting this as a hypothesis it is suggested that the value of this approach will be tested. That is currently not being done.

We have removed this second hypothesis.

Methods:

Page 3, line 19: I would appreciate a section on the data, or more information on the data at least. How many bursts do you have for your study region (on the map we currently only see those that

have led to a cascading event)? How many of these are in sandy soils? What percentage of those that are not on sandy soil have led to cascading events? This comment also holds for the news items. You mention 30+ reports, but is this for 30 different events? How many of these were on sandy soil?... After the section 'methods' I remain with the question whether you have information about all bursts or only about those that led to a cascading event. Do you not have a problem of selection-bias in your sample (eg soil types that have a better water evacuation not leading to cascading events being underreported in the number of bursts)?

We have included a new section (2) on data. In addition we have reduced discussion of data that was subsequently not used to a negligible level, so there is greater focus on the data that was used. The flow of data has also been clarified in Figure 1.

Page 4, line 5: I am a little surprised about this sand map. First, at several places in the manuscript it is mentioned that a soil map was created (abstract, or page 20, line 2), while I guess soil maps were already existing. For this manuscript a reclassification of soil groups was just ran based on sand content. I might be wrong, but this does not seem very new to me and it shouldn't be presented as a main contribution of the manuscript. The manuscript makes other contributions. If more than that was done, this should be mentioned here.

The sand map was a re-classification of existing maps combining a number of data layers, and we have made this clear in the manuscript. We have reduced the emphasis on this part of the work.

Page 5, line 2: It is mentioned that for consistency sand content at 80 cm depth was used. But were other depths also tested during robustness checks? In other words, are the results robust to alternative classifications of the sand map? If so, please mention this. If not, in the discussion please elaborate on why this is not the case and explain why 80 cm depth is the most relevant depth.

Other depths were investigated in the initial exploratory analysis, but we quickly settled on the 80 cm depth as this is most representative of water pipe depth in the UK. We have removed reference to the other depths in this paper for clarity.

Page 5, line 8: As mentioned earlier, I find it hard to understand and evaluate this section because I do not have a clear overview on the data that were used. Why was it chosen to limit method 1a to Lincolnshire only?

Lincolnshire Roads: We only had road data for the one county, so this is why it was limited to this area. We have also made this more clear by amending Figures 1 and 2. In addition, for clarity we have renamed methods 1a and 1b as Methods 1 and 2. So now Methods 1, 2, and 3 are all geospatial analyses and Method 4 (previously Method 3) is the Workshop / interviews. This also clarifies the flow through the paper in the results section.

Page 5, line 22: It is not clear to me how the road can be improved by a burst water main. Except due to good reparation of the road. This section (as well as the section on page 6, line 11) also causes some confusion to me because it reads as if changes in RCI were used to identify bursts of water

mains. From later sections I understand that information on burst water mains is available from other sources as well, but I think that this section (page 6) should be rewritten.

Yes, road surface quality can improve after a burst as it can force remediation of the surface. We have re-written this section (p 7 lines 24- page 8 line 2)

Page 7, line 3: What about the directionality of causality here? How can we know that it is the previous burst that causes the next one, and not a common cause, like for example pipes being old, or slow onset landslides? This could be a problem in the current approach.

We agree. The data says nothing about cause of the failure, so we are using a mixture of knowledge of system failure mechanisms and data to support our comments in this section. We have mentioned the different possibilities in section 3.2 (page 9, lines 1-4)

Page 8, line 1: Like for the two other methodologies, it is important to mention the sources of information here. How many workshops were held, with how many participants? What were their roles and functions and what is the gender balance? Which questionnaire, or form to guide the discussion, has been used? Could this form be added to the appendix?

We have described the workshop design, approach, and analysis in more detail in section 3.4

Page 8, line 6: Did you do these workshops before or after the previous analyses? I.e., did you yourself already have information about the topic during these interviews? How did you make sure not to influence the outcome?

These workshops and interviews occurred following initial work in the other three methods. We have clarified the approach to sharing of the results in figure 1, and in section 3.4 (page 10, lines 8-10)

Page 8, line 9: What is meant with a 'thematic analysis'? How was this analysis done? More care needs to be given to the collection and interpretation of the data if social sciences methods are to be used.

Our approach has been clarified in Section 3.4, page 10, lines 16-20.

Results and Discussion:

Given the current objective of this manuscript (i.e., the second objective being to test whether a mixed method has an added value), in this section I would not present the results of all methods confounded because that prevents us from appreciating and evaluating the added value of a mixed method approach. I would start by discussing what was learnt from each of the methods, then what would be missed out if the other methods had not been used. Then discuss your overall finding from

the integration C4 NHESSD Interactive comment Printer-friendly version Discussion paper of the different methods and use this as an illustration of the value of mixed method approaches.

We have revised the results section as you suggested, to consider each method individually, before integrating our discussions.

Page 8, line 16-line 24: Some of these would better fit in the materials and methods section, I think. These lines are still providing information necessary for the interpretation of the results, not yet the results themselves.

We have moved the section as indicated.

Page 9, line 6: It is not clear to me why different scales have been used for the different methodologies. If this one is over whole of England and Wales, why is the other only on one tiny subsection? Please discuss how the difference in scale has a consequence for the comparison of the different methodologies.

We have clarified the difference scales used in the different methods in figures 1 and 2. Different scales were used due to different data availability. As each method is carried out in its own study area the results are not meant to be explicitly compared, but rather, together they build a body of knowledge, from different perspectives around this theme of impacts from burst mains.

Page 12, line 5: Could it be that what is actually measured here is the quality of the reparation works, rather than the impact of the bursts? What is the relevance of this? Wouldn't it make more sense to use municipal data on the costs related to reparation works as a measure of the impact? Secondly, I am not sure about how the spread in road quality after a burst in sandy soils indicates that greater remedial work is required... Also it is not clear whether the difference in spread is significant.

We have clarified the scenarios in which we feel the road quality can change in section 3.1, page 10, lines 23-30). Because we were analysing the road quality in proximal areas which had, and had not been influenced by a burst, the change in RCI, if higher in sandy soils, might reflect that more damage was inflicted on the road, thus requiring more substantial remedial work (rather than a standard cut / replace just to access a burst main.) Because of the very large number of observations, the difference is statistically significant. However, we do recommend caution in drawing strong conclusions from the analysis in isolation (page 11, lines 6-9). This is another benefit of a mixed methods approach.

Page 13, line 2: It is not clear to me how you come to this. I think that from the data it is not possible to conclude that the roads are being repaired to a lower standard. the averages did not differ. To my understanding, the following result is also not warranted by the data: "Trenching will also provide preferential hydrological pathways for water compared to the surrounding ground.". How has the analysis led to this result?

This comment was made by a highways engineer in Method 3, and is not derived from the data analysis, so have removed it from this section. This view is supported by comments (p17, lines 13-14)

Page 14, line 1: It is not clear whether this has been observed in the study, whether it comes from other reports or whether it was mentioned during the workshops. Also the added value to the study is not clear

This was discussed at the workshop and investigated in subsequent research. The reason we have included this is to highlight that a gas leak is more serious health risk than the original water leak. We have clarified the source of this comment.

Page 14, line 18: I think the findings in this section are worth further elaboration and further study. This could be an interesting added value to literature!

Thank you. We will consider a more detailed investigation in the future.

Implications:

Page 18, line 19: To me, it seems that a qualitative assessment was done of the impact, rather than a quantitative assessment.

We have rephrased this as requested. We used quantitative and qualitative methods, but the integration of these does come to a more qualitative conclusion.

Minor Comments:

Title: I would slightly change the title, because its current form is not easy to read. By writing "the influence of . . . on . . . of . . . on . . ." it is not immediately clear the influence of what on what is being studied. After rereading it is clear that you measure the influence of soil on the relation between burst water mains and consequences for society, but this should be clear from the start.

We have changed the title as requested.

Page 2, line 10: I would appreciate additional explanation for this term which is new to me: "siloeed approach".

We have removed this unclear term.

Page 2, line 21: I am not sure whether this paragraph perfectly fits here. Maybe move it up, just before previous paragraph.

We have moved it as requested.

Page 2, line 27: Add apostrophe: organisations'

Done, thank you.

Page 3, line 13: While I am not an expert in this, I am surprised by this first hypothesis. I would expect a sandy soil to be more porous to water, thus more easily evacuating leaking water and less likely to cause cascading events.

We have tried to clarify our thinking behind this hypothesis here and throughout the paper.

Page 6, line 7: I don't understand what is meant with "To mitigate this spatial inaccuracy, a count of these polygons was used in this context simply to calculate a change in condition."

We have clarified our explanation (p 8, lines 8-11) with reference to the green polygons in Figure 3.

Figure 4: Please mention total amounts somewhere, not only rates. Also report confidence bars in two subgraphs. In the caption, mention which of the subgraphs is national A, B and unclassified.

This is now Figure 7. We have clarified what this graph is showing. These are all national assessments from the media analysis.

Page 13, line 22: (300, 400, 800 homes in media reports) = What is meant by these numbers and could it be possible to add a reference?

These numbers refer to the number of homes referenced in the media analyses. These references are provided in the Web References section, and Appendix A.

Page 16, line 3: "A large water company invested a large amount of money cleaning sand from the sewers in Lowestoft, only for the sewers to fill up with sand again following the next storm surge." This is an interesting fact, but it doesn't seem relevant for the case study at hand.

We have removed this "interesting fact".

Page 19, line 6-9: It is also not totally clear to me how this information helps us to test the hypotheses that were proposed in the introduction.

We have removed this.

Page 17, line 17: "This research identified mixed levels of awareness of sand washout risk from infrastructure operators." This is an interesting finding, but it seems to fall outside the scope of the objectives of the manuscript, I think.

We have removed this comment

Page 18, line 1-2: I wonder, after this study, whether you could say whether it is worth, from a cost-benefit point of view to collect such detailed information?

We have not undertaken a cost benefit analysis here. Given our experience of working with utility companies, changing the collection of any data is a challenge!

Page 18, line 31: This was not totally clear to me from the results.

We have tried to clarify our thinking on this point.

Page 19, line 15: The study did not focus on the UK, but on a much smaller area, I think.

There was a UK focus for the media analysis and the workshop / interviews, but also with more detailed regional sections. We have adapted the comment to reflect this.

Page 20, line 2: No soil maps were created, to my knowledge.

We have reduced the emphasis on this point.

Many thanks for your helpful comments.

Thank you,

Tim Farewell, Simon Jude, Oliver Pritchard

The influence of soil on How the impacts of burst water mains on infrastructure and society: A mixed methods investigation are influenced by soil sand content

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Abstract. Society relies on infrastructure, but ~~collocation and interdependencies make~~ infrastructure systems are often
10 collocated and interdependent, they are vulnerable to cascading failures. This study investigated cross-infrastructure and
societal impacts of burst water mains, with the ~~hypotheses~~ hypothesis that ~~1) burst main triggered cross~~ multi-infrastructure
failures triggered by burst water mains are more common in sandy soils ~~and 2) mixed methods approaches are more beneficial~~
~~than pure data analysis for understanding the wide ranging impacts of these events~~. When water mains in sandy soils burst,
pressurised water can create sub-surface voids and abrasive slurries, contributing to further infrastructure failures. ~~To~~
15 ~~investigate~~ Three spatial data investigations, at nested scales, were used to assess the role of soil influence that soil sand content
has on the frequency and damage caused by burst water mains 1) to roads in ~~hosting cascading~~ the county of Lincolnshire. 2)
to other proximal water mains in East Anglia, and 3) to other proximal infrastructure ~~failures, maps of soil sand content for~~ and
wider society across England and Wales ~~were created. Analysis of the. These investigations used~~ infrastructure impacts arising
from burst mains combined; 1) spatio-temporal clustering and analysis of infrastructure network and failure data, 2) meta-
20 analysis of web based media reports of burst mains impacting on other networks, and 3) 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 ~~spatio-~~
~~temporal data~~ 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.

25 **1 Introduction**

The socio-economic and physical wellbeing of society is increasingly ~~dependant~~ dependent on infrastructure services (Lloyds
Register Foundation, 2015; Guikema, 2015; Defra, 2013) ~~and infrastructure~~. Infrastructure assets (e.g. pipes, cables, roads,
substations, pumping stations and buildings) are commonly co-located. ~~Consequently, 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 ~~The~~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 ~~further~~ complexity for infrastructure operators and regulators tasked with providing robust and resilient levels of service \(Rinaldi et al., 2001; Rogers et al. 2012; Chalker et al., 2018\). With the limited awareness amongst infrastructure asset managers of system-of-systems thinking, which is rarely employed in asset risk assessments, and the ~~“siloed” approach of limited communication between operators,~~ governments and regulators, understanding of infrastructure interdependencies is often lacking \(Young and Hall, 2015; Defra, 2011; Jude et al., 2017; Street et al., 2017; Committee on Climate Change, 2017\). \[Indeed, the second UK Climate Change Risk Assessment \\(CCRA\\) identified cascading infrastructure failures as the highest risk facing UK infrastructure \\(Dawson et al., 2016\\). Furthermore, the CCRA recommends greater consideration of subsidence risks to infrastructure, and improved risk-information sharing between infrastructure operators \\(Dawson et al., 2016\\).\]\(#\)](#)

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~~An example of how water bursts can impact on other infrastructure networks occurred in Matlock, Derbyshire, UK, (BBC, 2013a). 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, and the County Hall suffered flood damage (including to official records) and was closed for days. This one 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 were much higher.~~

~~Natural~~ such infrastructure risks is that natural hazards to the built environment have different frequencies, impacts and spatio-temporal scales. ~~A~~ In particular, whilst a considerable body of literature exists surrounding acute environmental hazards such as flooding (e.g. Bowering et al, 2014). ~~However,~~ less research explores more complex, and often chronic, forms of soil-related natural hazards and related infrastructure failures (Defra, 2011). Such hazards pose ~~significant~~ substantial risks to infrastructure systems that may be currently underestimated by stakeholders. Because risk-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 ~~are~~ may not be high on ~~organisations~~ 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 soil types.

~~Sandy soils have~~ sand contents. Of particular concern are sandy soils with greater than 70% sand-sized particles (0.06-2mm) ~~and~~. Whilst sandy soils cover less than 20% of England and Wales ~~(Cranfield University, 2016)~~. They, they are susceptible to water-assisted erosional processes and are not uncommon in some urban settings (Brink et al. 1982). ~~Water; Cranfield University, 2016)~~. Thus, water escaping from buried pipes can form voids, removing the structural support normally offered by soil to infrastructure (bridging), while also forming). In addition, sand and pressurised water can form abrasive slurries which are highly damaging to proximal plastic pipes (Majid et al., 2007).

~~The second UK Climate Change Risk Assessment identified cascading infrastructure failures as the highest risk facing UK infrastructure. The assessment recommends greater consideration of subsidence risks to infrastructure, and improved risk-information sharing between infrastructure operators (Dawson et al., 2016).~~

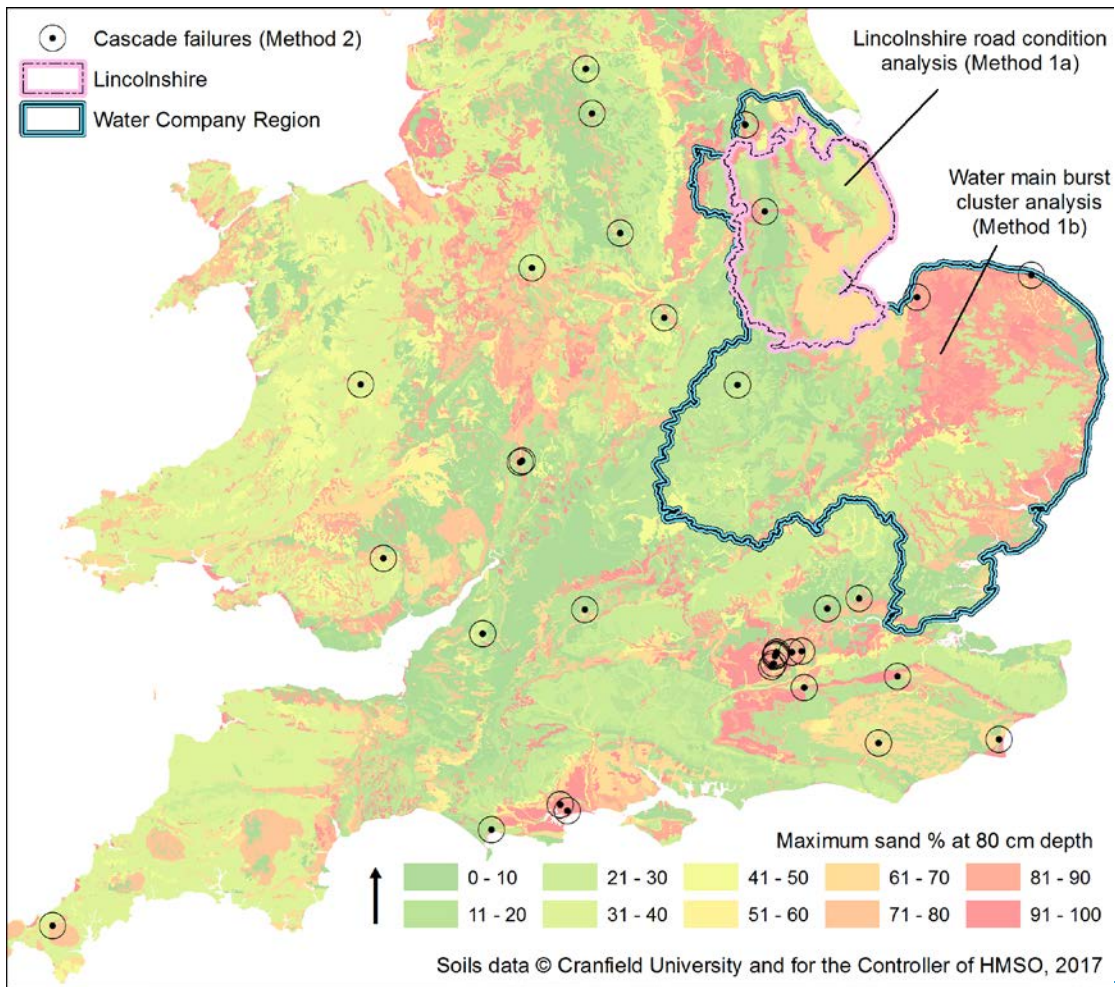
This paper presents an interdisciplinary scoping study exploring the ~~impact~~ influence of sandy soils on the impacts of burst water mains on physical infrastructure (electricity, natural gas, water, wastewater, transport and telecoms), public service

infrastructure, (government, emergency services, healthcare and education), and wider socio-economic functions. The hypotheses are twofold: 1) That sandy 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 lead to damage of proximal infrastructure. 2) That a mixed methods approach will be more beneficial than purely quantitative data analysis for understanding the wide-ranging impacts of these events. Four methods and multiple sources of evidence are used. Discussion focuses on the impacts of these failures on burst water mains on different infrastructure systems and wider society, as well as methodological approaches and the risk management implications of this research.

2 Methods

10 The control of

Three spatial data investigations, at nested scales, were used to assess the influence that soil sand content has on the impacts of frequency and level of damage caused by burst water mains on: 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 was investigated with three methods, in three study areas. These include: 1) quantitative spatial data analysis of industry reported infrastructure failures for a local authority region (1a) and water company region (1b) in the East of England; 2) meta-analysis of media reported multi-infrastructure failures and wider society across England and Wales; and 3) a workshop and (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 UK 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 regional study areas (Fig. 1) were guided by the availability of infrastructure data of sufficient quality and quantity.



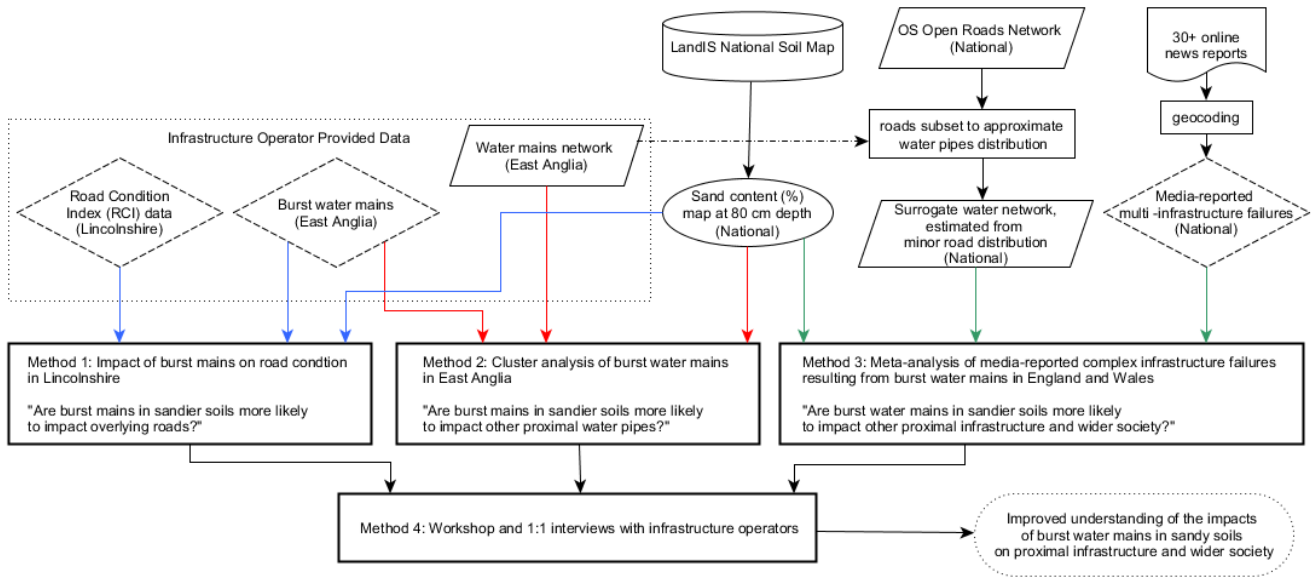


Figure 1 — ~~Maximum~~ The flow of data and information between the methods

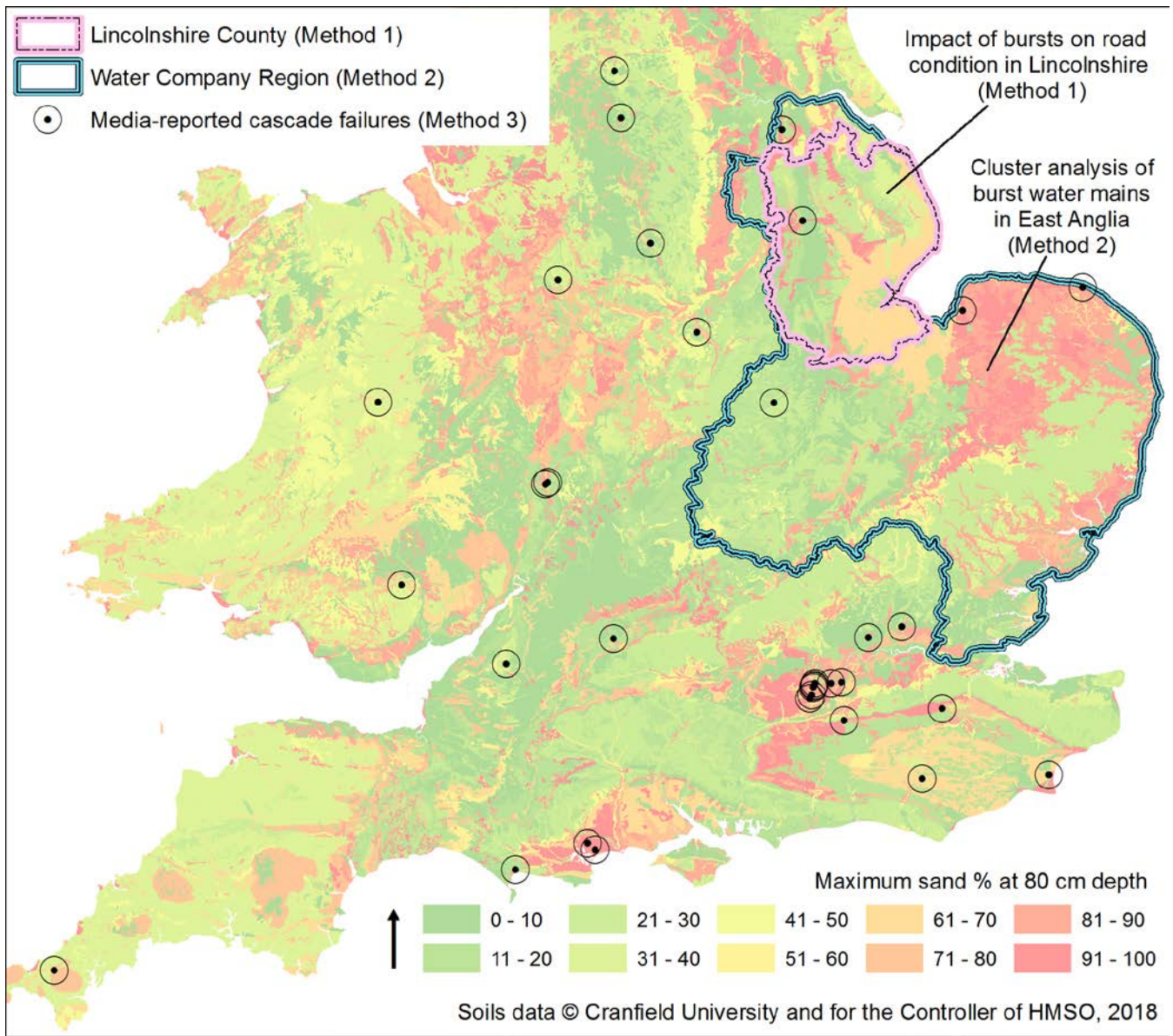


Figure 2 – Map of maximum sand content map at 80 cm depth for England and Wales, with the study areas for the different methods, and media-reported cascade failures, which are described in detail in Appendix A.

2: Data

This study required data on ~~1-Sand content maps~~ 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 %.

Maps of

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 using 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, so multiple sand content maps for minimum, (which comprise numerous soil types). The maximum and weighted average sand content at 0, 40, 80 and 100 cm depth were created within the soil mapping was chosen instead of the mean to reflect the variability of soil sand content associated highlight areas with common infrastructure burial depths. In this paper, for consistency, the maximum sand content at 80 cm depth (which approximates water pipe depth) is used even small areas of sandy soil, and to minimise the over-mapping of loamy soils which results when soil textures in all analyses regional soil textures are averaged.

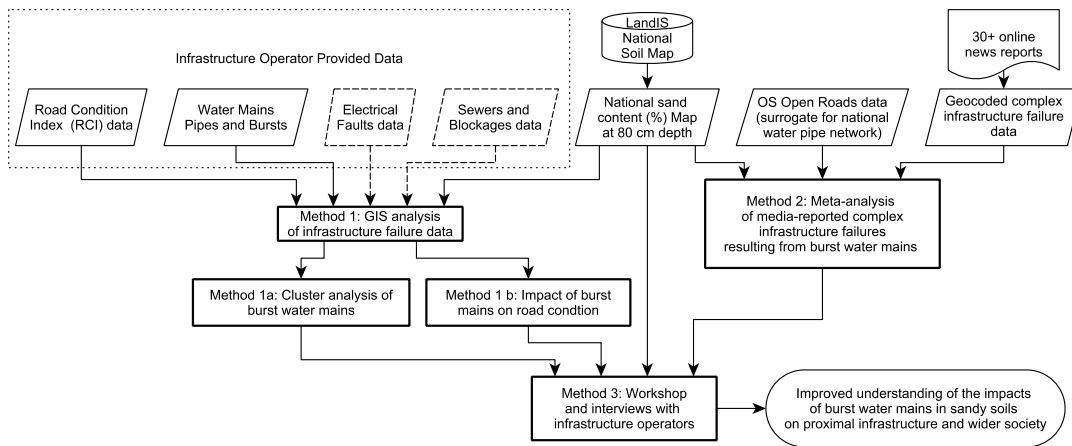


Figure 2—3 Methods

The flow of data and information interactions between the three methods. Note: Dashed lines indicates datasets which were collected but not of suitable quality for use in the analyses.

2.2 Method 1: GIS spatio-temporal cluster analysis of infrastructure failures

An analysis of infrastructure failures was undertaken in two, their study areas in the East of England for which detailed asset and the data used is summarised in Figures 1 and failure data was available (Fig. 1). Infrastructure asset and failure data was obtained from water, sewerage, road and electrical infrastructure operators. Electrical and sewerage fault data were discarded as they were of insufficient accuracy for spatial analyses. Thus, the analysis focussed on assessing the impact of burst mains on roads (Method 1a) and the impact on other water pipes (Method 1b).

2.2

3.1 Method 1a: Measuring 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 survey data collected before, and after, reported bursts-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. 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) to 315 (failed) (Wallis, 2009; UK Roads Board, 2011; Pritchard et al, 2014b, 2015b). 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.

~~Roads with RCI >100 require maintenance. RCI change after a burst was calculated and analysed in the light of 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.~~

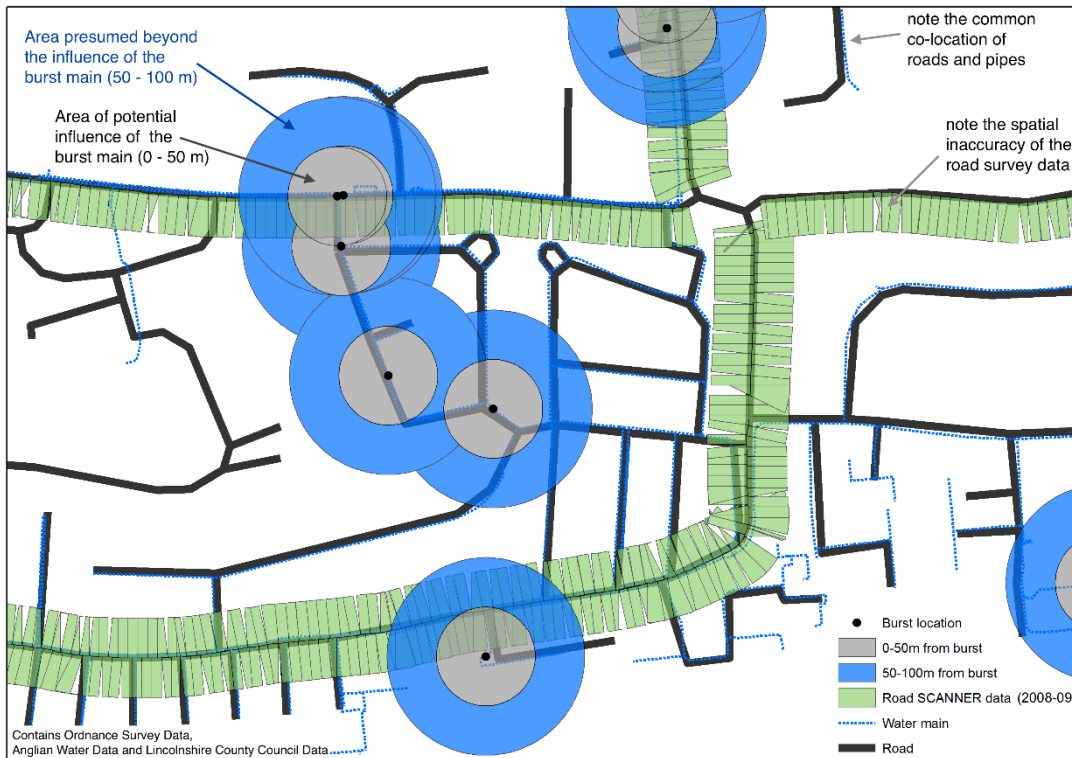


Figure 3 – Example region showing road sections which potentially have been influenced by a burst, and the similar road sections which are presumed beyond the area of influence (Method 1a). Burst data from the water company; Road data from the Local Council.

- 5 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 wide, and in length, but the GIS representation of these lengths (inaccurately) extend well beyond the road footprint- (green polygons in Fig. 3). To mitigate/minimise the impact of this spatial inaccuracy, a count (rather than the area) of these polygons was used-in this context simply, along with their RCI scores to calculate a change in condition between the survey dates before and after the burst.

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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

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~~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.~~

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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. 75). The calculation used is:

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

Where:

clusters_s = the number of clustered bursts within a sand decile

bursts_s = the total number of bursts within a sand decile

15 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)

2.2.2

3.3 Method 1b: Measuring the3: The impact of burst water mains on other water mains

~~To test if burst mains in sandier soils were more likely to trigger subsequent bursts, clusters of water main bursts were identified using expanding spatio-temporal windows: ((distance: 2, 5, 10, 30, 100 m) (time: 1, 5, 10, 100, 365 days)). These windows were chosen to capture 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. For instance, a road surface weakened from cutting to access the pipe, or due to voids, may increase variations in traffic loading forces on pipes; infrastructure 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.~~

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2.3 Method 2: Meta-analysis of media-reported burst water main events

society

30 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 ~~main events~~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). ~~Bursts~~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 ~~information from the soil~~ sand ~~maps~~content.

~~To calculate normalised rates of failure (e.g. bursts per 100 km of pipe), the length of water mains in each soil map unit across the UK (Fig. 1) was estimated using the OS Open Roads data (“A”, “B” and “Unclassified” Roads) as a surrogate (OS, 2016). This results in a 7% underestimate of the length of pipe in East Anglia (39669 km roads vs 43000 km pipes). This error is sufficiently small for the purposes of this research, and no spatial bias in the linear infrastructure data was observed.~~ 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 ~~is~~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.

23.4 Method 34: 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 ~~elucidate~~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. ~~Discussions~~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. ~~The, and notes or audio recordings of the discussions were collected. Established analytical methods were employed to analyse the~~ workshop notes and interview transcripts ~~were analysed using thematic analysis to identify key themes.~~

3 Results and Discussion

This section provides combined results and discussions from all three methods. First, the control of soil sand content on the rate of cascading infrastructure failures is discussed. Then, the impact of burst water mains on other infrastructure, and wider society, is investigated. Implications of this scoping study for risk management are then discussed. Finally, the mixed methods . with an interpretive approach is assessed. The media meta-analysis (Method 2) and the workshop / interviews (Method 3) revealed, based on inductive insights into from the data, used (Saldana, 2009). This involved the manual coding of the data, resulting in the wider impacts of water mains on other infrastructure that were hidden from the pure spatial data analysis (Method 1).

The workshop and interviews provided a framework for extracting infrastructure operators' perspectives on cross-infrastructure impacts of burst mains. Network operators described these 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) but the value of cross sector regional task groups was asserted. inductive identification of key themes and sub-themes. Details from these discussions are illustratively incorporated in this section. the results and discussions. For brevity, citations of comments from the workshops and interviews, and the meta-analysis media articles, are omitted from the text. The media articles are summarised in Appendix A discussion text.

4 Results

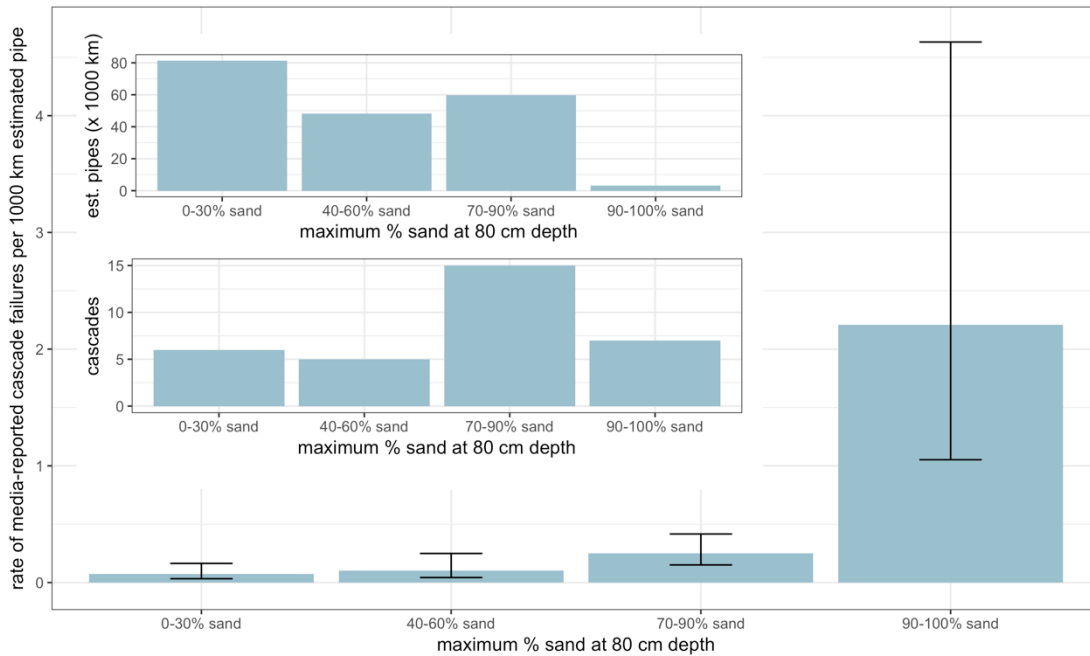
The results of the methods are briefly described below and in more depth in the Discussions. Where figures include error bars, they show the 95% confidence intervals for the poissonPoisson mean. This interval is calculated by transforming a symmetric 95% confidence interval (CI) for the logarithm of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

3

4.1 Method 1 Results: The control of soil on the location of cascading infrastructure failures

The rate of impact of burst water mains bursts does not appear to be controlled by soil sand content. The four bands of sand content in Fig. 4 all have a very similar rate of bursts of between 0.97 and 1.05 bursts per km of pipe. However, the meta-analysis indicated that sand content does play a controlling role in the likelihood of an initial burst going on to impact on other infrastructure. A higher rate of media-reported cascading infrastructure failures was observed in sandy soils (Fig. 4). 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.

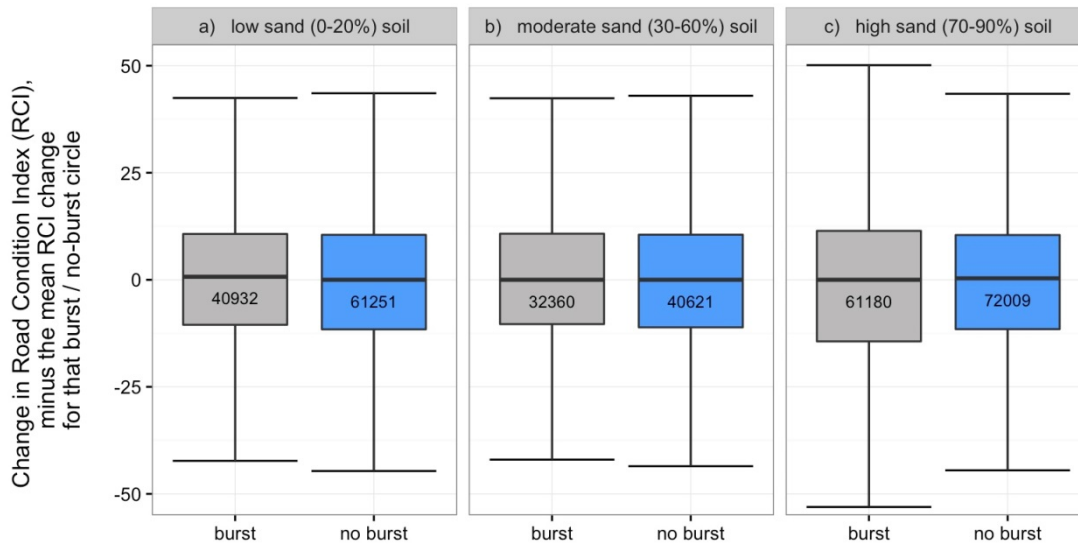


Figure 4 - Comparison of the change in RCI before and after a burst water main (minus the mean RCI change for the circular sample area (Fig. 3). The numbers on the box plots represent the number of analysed road segments. Whiskers: Range excluding outliers (IQR +/- 1.5*IQR).

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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. Rate of media-reported While the smallest spatio-temporal window shows low rates of cascade failures, 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.

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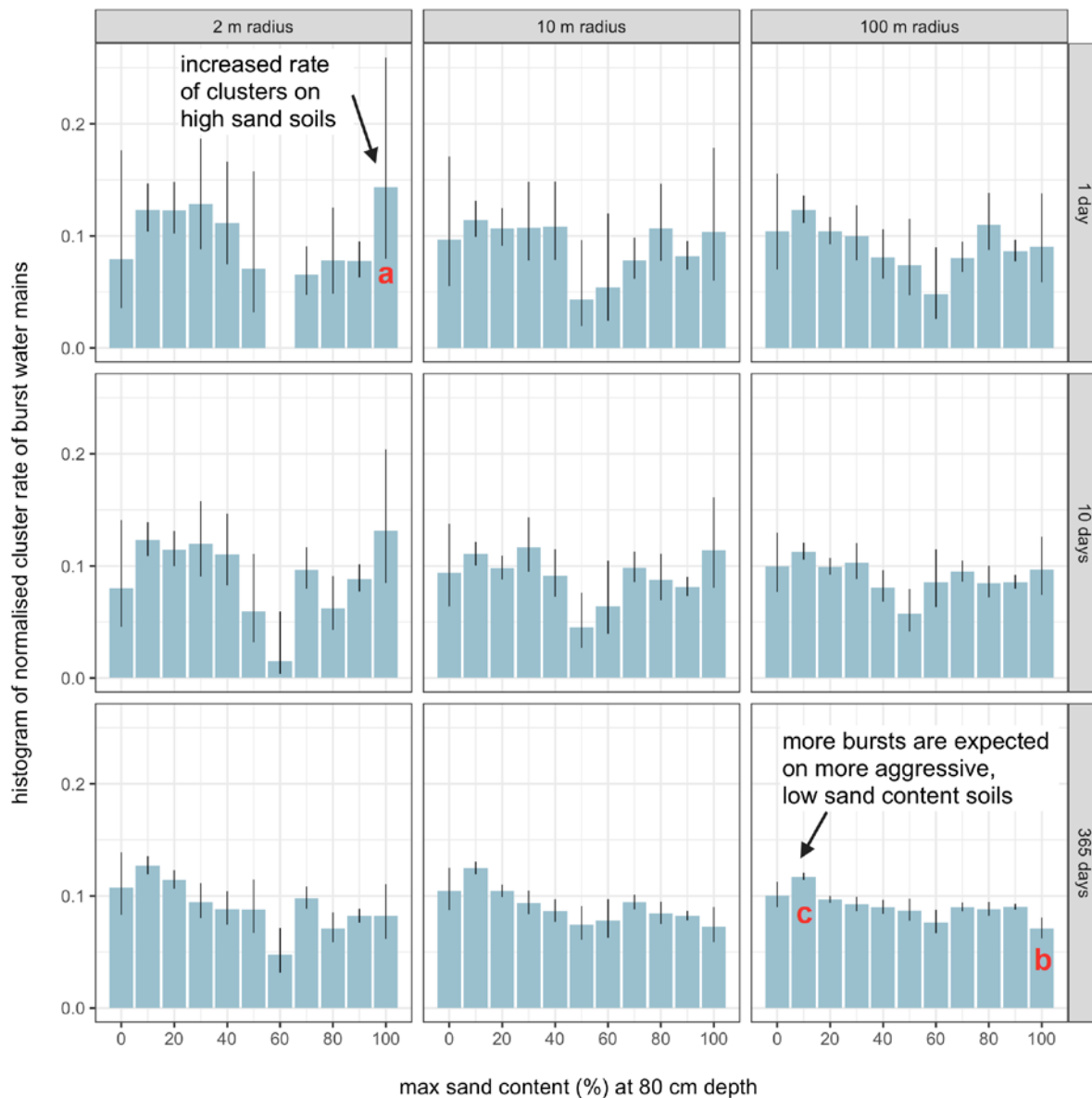


Figure 5 - normalised by pipe distribution (estimated from national A, B and Unclassified road length) in each soil type, rate of (burst cluster) / (all bursts within expanding spatio-temporal window), by maximum soil sand content at 80 cm depth. Error bars (-): 95% CI for the Poisson mean. Higher bars indicate more clusters of bursts per initial trigger burst. For clarity, only 9 of the 25 spatio-temporal windows are shown (Confidence Interval for the poisson mean).

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4.3.2 Method 3 Results: The ~~impacts~~ 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. 4). The articles (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. 56 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).

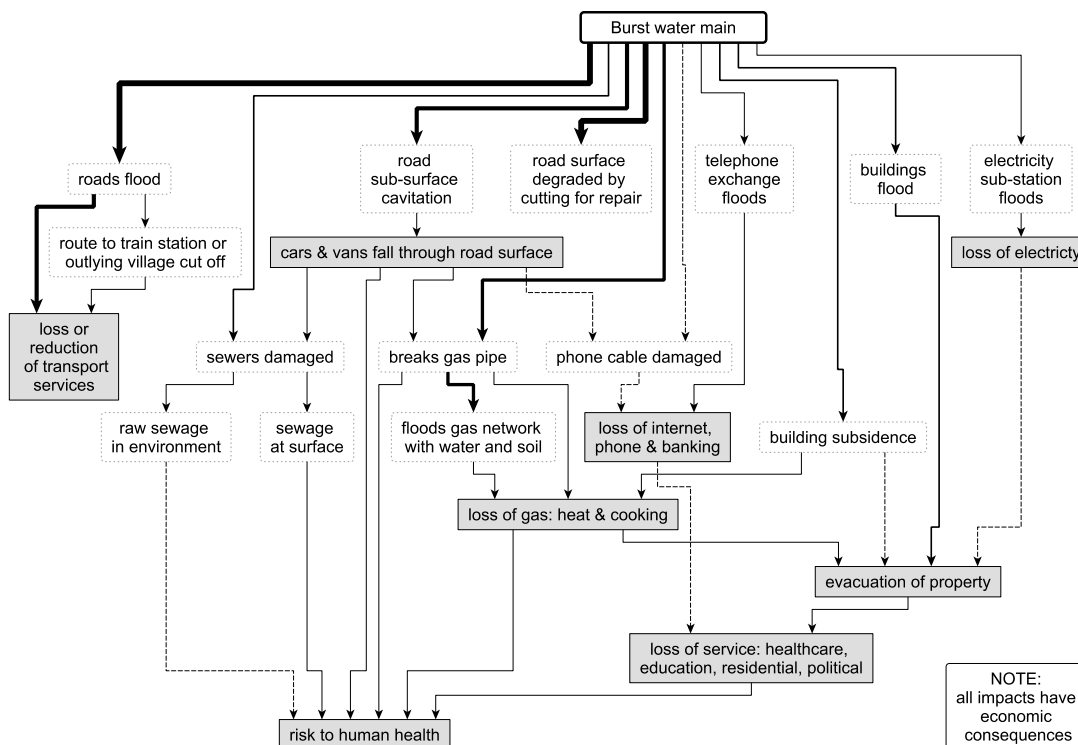


Figure 6 – Summary of impacts from burst water mains on other infrastructure and wider society. Schematic diagram based on analysis of 33 media reports, workshop discussions and interviews, showing impacts to other infrastructure and society. Line width represents the relative frequency of the impact.

|

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.)

5 **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.](#)**

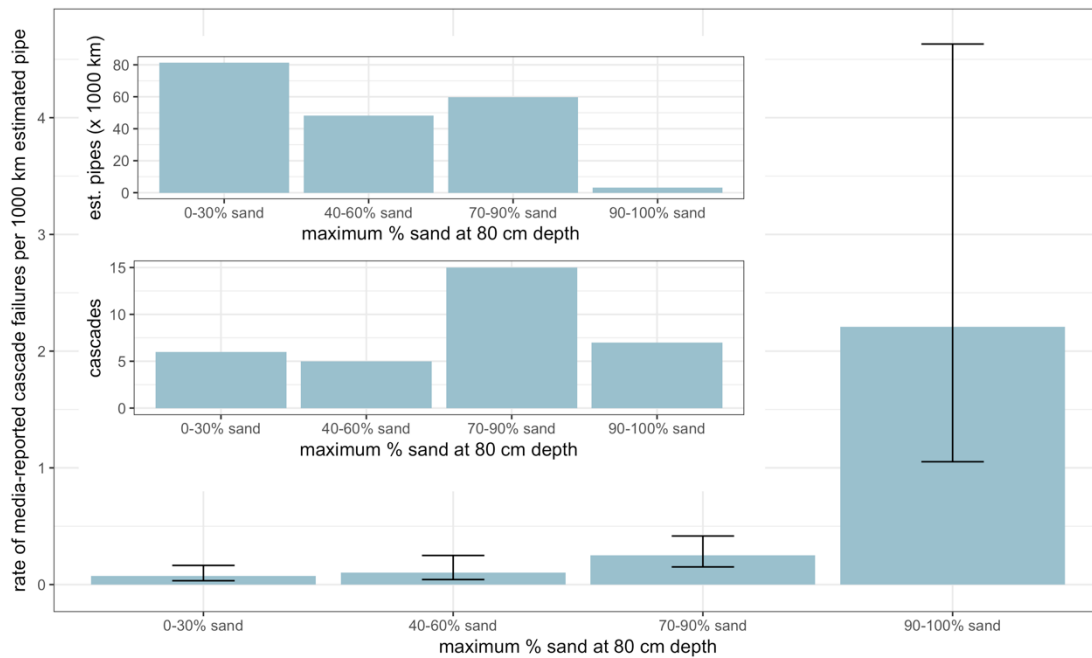


Figure 7 – Main figure: Rate of media-reported cascade failures, normalised by estimated pipe length in each soil type. Error bars (95% confidence interval for the Poisson mean). Top inset: Estimated pipe length across England and Wales, by sand content. Bottom inset: number of media-reported cascade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

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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

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., Note: where reports indicate a range (e.g. 8-11), this is due to uncertainty in the descriptions provided by the media.

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3-22016) 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.

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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 are less well-engineered, 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 ~~on~~under a ~~major~~ 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.

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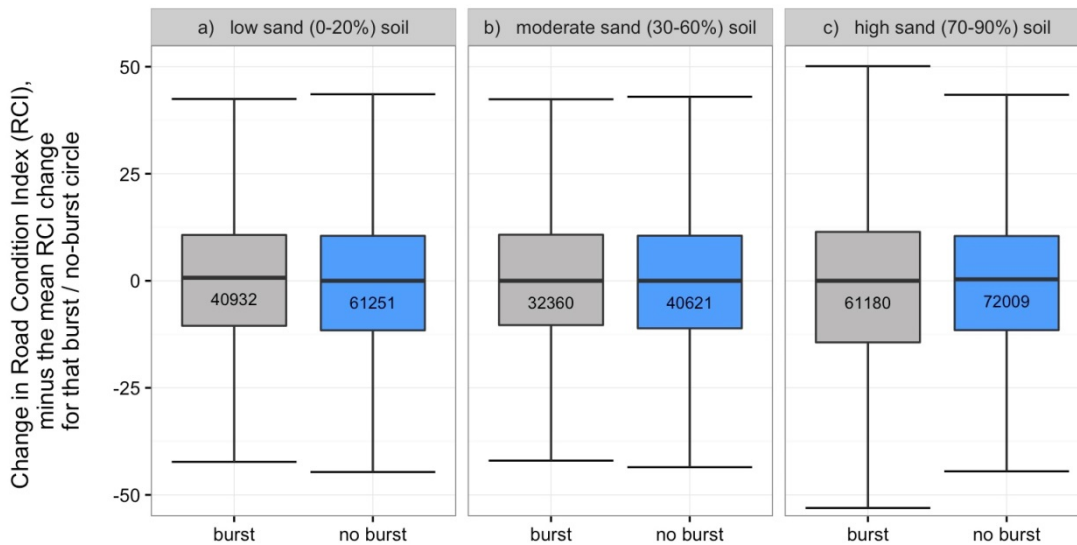
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Road damage or flooding can extend travel times and distances and can result in reputational damage to the water and highway operators. Diversions in rural areas of up to 48 km were identified. Bursts. Major voids will lead to longer road closures,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

5 In the water company region (Fig. 1), 93% of minor (D) roads have pipes within 16 m of the centre line of the road. It is logical that a failure in the pipe network will impact directly on the road, through void formation, or indirectly through road cutting to access and repair the pipe. To test this, the change in road condition was assessed (prior to, and after a burst) using annual road condition (RCI) surveys for 232897 road segments “potentially influenced” (0-50 m) by a burst main and 262140 segments deemed “beyond influence” (5-100 m) of the burst (Fig. 3).

10

With only one exception, for all roads, the mean RCI change was approximately 0 (Fig. 6), with consistent interquartile range (IQR) for all roads. However, roads built on sandy (70-90%) soils, within 50 m of a burst main, showed greater spread in the change in road condition, which indicates that greater remedial work is required to roads following a burst in sandy soils.



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Figure 6 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).

20 Thus, 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) and

- ~~this). 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. ~~Because the road surface is repaired to a lower standard than that of the original road, as well as the subsurface. Cuts and trenches are well known to lead to subsequent pot holes or surface, the deformation features, including differential settlement. It was reported by highways engineers that cut roads not only have~~
- 5 ~~a shorter serviceable life-of the road leads to-, with higher maintenance costs-for councils. Trenching will, but also provide preferential hydrological pathways for water compared to the surrounding ground. Local highways engineers noted that road that~~ cuts may be contributory factors to subsequent water pipe failures at the same location ~~which are commonly reported within 1 year.~~
- 10 Where ~~non-catastrophic~~ 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 the initial misdiagnosis and repair of a small road surface deformations only to find a much larger deformation (or hole) the next day.

3.25.2 Ports and railways

- 15 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
- 20 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.

3.25.3 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.
- 25 Such failures commonly cause neighbourhoods many hundreds of houses to lose gas supply (~~300, 400, 800 homes in media reports~~Appendix A).

- The cost of ~~pipe-repairs~~ isto gas pipes is reported to be insignificant compared to the cost of removing water and sediment from ~~the gas~~ pipes. In some reported cases, up to 10,000 litres of water and debris needed to be pumped from the gas network.
- 30 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.

Health Workshop discussions also highlighted that health risks are higher when gas in buildings (GIBs) events occur, following a leak. These can occur, 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 mains through cracks in 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.

10 3.25.4 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, 80008,000 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.

3.25.5 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. 7-5, 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.

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. When the patterns in those two windows are compared, (Fig. 7) the smallest windows shows a higher rate of clusters in the sandiest soils, but also a high rate for the low sand soils— probably indicative of common cause failures associated with clay soils (e.g. corrosivity or shrink-swell). These clusters in the low sand content soils increase with expanding windows reflecting the larger number of bursts in these corrosive and movable soils.

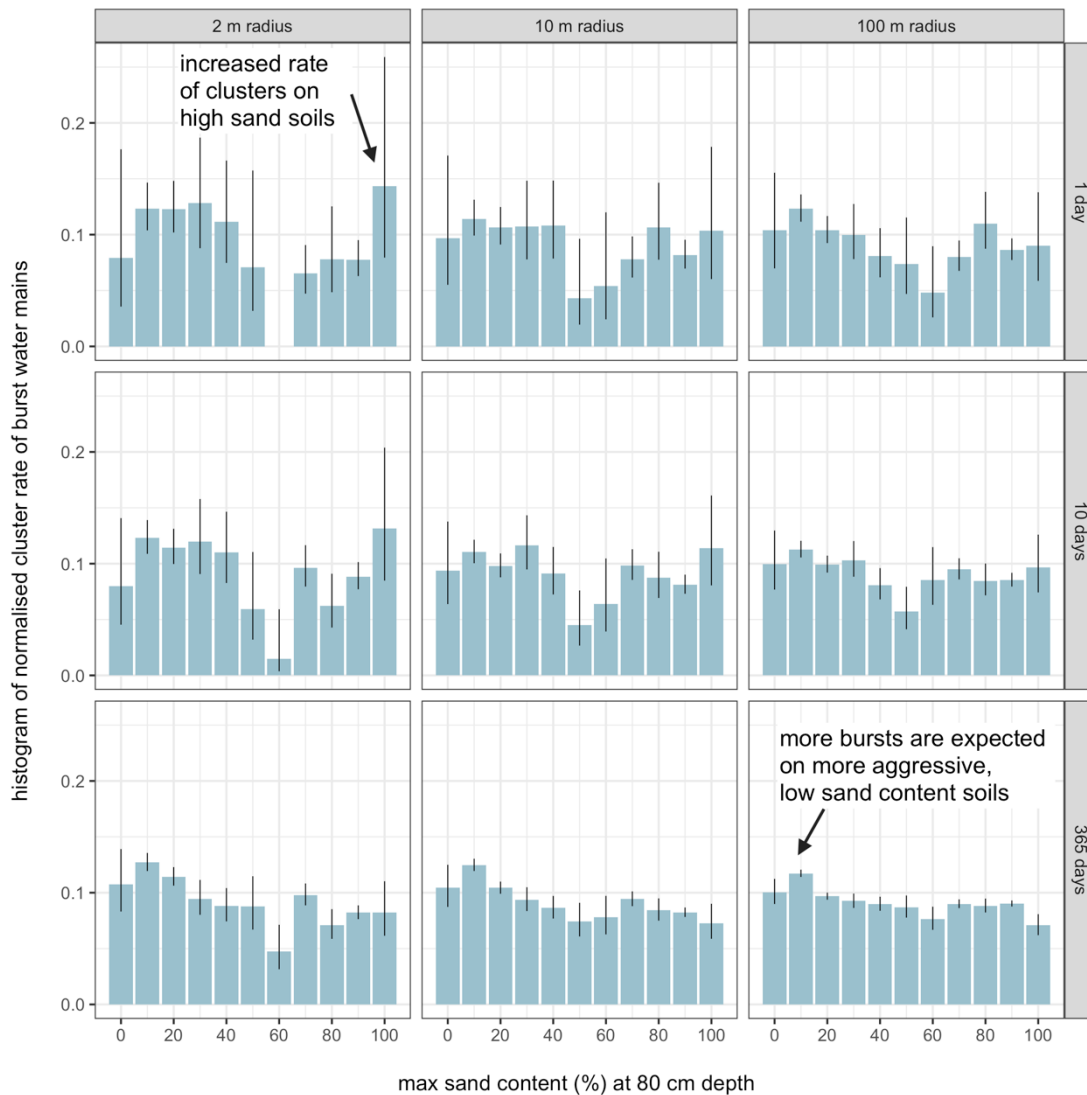


Figure 7 – normalised rate of (burst cluster) / (all bursts within expanding spatio-temporal window), by maximum soil sand content at 80 cm depth. Error bars: 95% CI for the poisson mean. Higher bars indicate more clusters of bursts per initial trigger burst. For clarity, only 9 of the 25 spatio-temporal windows are shown, but the full graph is provided in Appendix B.

5 3.25.6 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 [are without](#) 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 or, natural events such as storm surges, or high rainfall events. ~~Sandy~~Due to their non-cohesive texture, sandy soils are more likely to be washed into the sewers than clays and loams. ~~A large water company invested a large amount of money cleaning sand from the sewers in Lowestoft, only for the sewers to fill up with sand again following the next storm surge.~~

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.

3.25.7 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 ~~had~~was reported to have suffered two floods in two years resulting in £1m costs and subsequent relocation of equipment. Any disruption to electricity supply ~~has~~can have wide impacts, including ~~on small~~to IT networks.

~~Only minor impacts~~Impacts on electricity distribution networks from sand-washout events were less frequently identified, with 12% of media reports mentioning electricity distribution impacts ~~(Fig. 5).~~. 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.

3.25.8 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.

3.35.9 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.

3.4 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). ~~Due~~ However, due to the distribution of sandy soils (Fig. 1), regional trends can be observed. ~~This research identified mixed levels of awareness of sand washout risk from infrastructure operators.~~ 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 ~~the~~ their low-frequency ~~of such events~~ make them difficult to consider as part of many asset management plans.

Infrastructure monitoring incurs large 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.

- 5 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. ~~Both bursts are~~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. ~~While this scoping, 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. 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)

30 **3.5.11 Assessments of the mixed-methods approach**

This scoping study sought to describe and begin to quantify the ~~impact~~impacts of burst mains on other infrastructure; and determine if ~~a~~society. A mixed methods approach ~~provided more information, rather~~ than a pure GIS data analysis of reported

infrastructure faults and failures. ~~Indeed, 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.

5 The spatial data analysis quantified the ~~impact~~control of soil on the impacts of burst mains on ~~proximal water mains~~road
surface quality (Method ~~1a~~1), and on the ~~condition~~likelihood of ~~the roads~~subsequent bursts (Method ~~1b~~1) ~~and how these vary~~
~~by soil type. The~~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.~~ Industry-reported data did not describe wider societal
impacts, nor the scale or cost of the failures. ~~Significantly, the~~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
10 A) provided qualitative descriptions of both infrastructure failures and the impacts on health, economy and people (~~Method~~
~~2~~2). Because media reports tend to focus on the larger bursts ~~than little leaks~~, the ~~results can be expected to be more dramatic~~
~~than usual. impacts are not representative of all bursts.~~ However, analysis of these reports identified that the rate of these ~~more~~
dramatic failures per 1,000 km pipes is higher in areas of sandy soils. ~~(Fig. 4).~~ Because of the depth of information gleaned
15 from this approach, media meta-analysis is encouraged for other studies of low frequency, moderate impact local
environmental risks, ~~but further.~~ 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 ~~3a~~3), captured detailed perspectives on these cascading
infrastructure failures and their impact on service delivery, costs, responses and management plans. The combination of these
~~three~~ methods led to more quantifiable, descriptive and useful results than would have been possible if each method was used
20 in isolation.

~~Adopting a mixed methods approach to research does bring its own challenges. The default skillset of a data scientist may not
be sufficient to cover the more qualitative aspects of research, so a multi disciplinary team is required. For example, vastly
different approaches to assessing the accuracy or bias of data are required for GIS data, compared to that obtained from local
25 media reports, or in a workshop discussion. In a mixed methods investigation, it is recommended that a shared vision of a
successful outcome of the research is defined near the start of the investigation so that all methods contribute towards this goal.~~

46 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
30 sand content (~~Fig. 4~~), (~~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~~ended 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, ~~and~~ 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.

~~Critically, the~~The research illustrates the potential value of mixed methods approaches to investigate such complex infrastructure hazards and risks. ~~Whilst the~~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 ~~the~~mixed methods ~~approach~~approaches holds great potential for infrastructure research, but such ~~mixed~~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 ~~developed~~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.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was supported by NERC [NE/M008320/1] and EPSRC/ESRC [EP/I01344X/1; EP/K012347/1]. The sponsors played no role in the study design or the collection, analysis or interpretation of the data, nor any role in the writing of the report or decision to publish these results. Enquiries regarding the data generated in this study

should be sent to researchdata@cranfield.ac.uk. This research would not have produced the insights without the generous provision of data, time and expertise from the utilities (water, gas, electrical distribution) highways (local and national) telecoms and railway organisations who provided invaluable input. The authors would also like to thank Caroline Keay and Ann Holden for their assistance in the creation of the new sand washout potential map and the cluster analysis tool, and Daniel
5 Farewell and Vern Farewell for statistical advice.

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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_miserably_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
