Stream and spring capture in combined sewer systems

by

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Thesis submitted for the degree of Doctor of Philosophy.

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May 2014

Abstract

Streams and springs have not only been buried below ground in culverts but in some cases have been connected into the combined sewer system. These “lost watercourses” contribute another source of clean baseflow to sewer networks, in addition to the widely acknowledged and researched infiltration-inflow, which is the unintentional ingress of clean groundwaters or soilwaters through pipe cracks and defective joints. Stream and spring capture, as a type of point source inflow to combined sewer networks, has received little specific acknowledgement by the water industry in the UK. The considerable efforts to tackle sewer infiltration-inflow may be confounded by this type of inflow.

A literature review identifies examples from the grey literature and from the few published peer-reviewed papers on this issue. It demonstrates that stream and spring capture occurs in many cities around the world, and arose primarily from the historical development of combined sewer systems. Streams and springs were either diverted to intercepting sewers or were themselves converted into sewers, which can make it difficult to identify capture, quantify the flow, and evaluate the true costs. Drawing on comparisons to infiltration-inflow, the review identifies the types of consequences of stream and spring capture, and demonstrates that this issue is worthy of further attention by the water industry.

Evidence that can be used to identify stream and spring capture is reviewed and demonstrated on a case study of Sheffield, UK. It is found that no single source of information can always be relied on to indicate capture. Instead, a multiple lines of evidence approach is proposed. This uses multiple desk-based information sources to reconstruct the likely locations of “lost” streams and springs, including historical maps and topographic flowpath modelling, finding that over half the stream length and over 100 springs are lost or buried in the 89 km^2 search area. It then presents multiple methods that can be used to indicate whether or not these “lost” streams and springs have been captured into the combined sewer system, and methods that can be used to confirm these indications. It confirmed that there are at least five sites where streams and springs flow into combined sewers to the WwTW.

A novel water typing method is developed that can be used to indicate stream and spring capture sites. Results of a detailed sampling program of five capture sites in Sheffield are

presented, with sewer samples taken during the night time minimum flow and daily peak flow morning periods. The method uses major and minor ions to differentiate distinctive chemical fingerprints ("water types") of spring and stream waters (reflecting local geology) and wastewaters (reflecting local tapwaters) and measures the downstream mixing between these end-points. Major and minor ion water types are shown to reflect sites of known capture, though this is limited to the sites of capture by interception where it was possible to separately sample and type the captured water, wastewater, and mixed water end-points separately. In one case, a combined sewer was quantified using major ion water typing as consisting of 60-90% captured watercourse flow during the daytime – a considerable proportion.

Finally, a Bayesian Belief Network (BBN) model is developed to separately predict where both stream and spring capture and infiltration-inflow are likely to occur in a sewer network. The BBN uses expert beliefs to predict the likelihood of stream and spring capture and infiltration-inflow from various sewer characteristics, such as pipe material and age, and proximity to recorded "lost" streams and springs. This therefore builds on the earlier body of work locating lost streams and springs to assess capture likelihood on a sewer-by-sewer basis. One purpose of this is to enhance understanding about whether and where stream and spring capture occurs, showing that in Sheffield it is expected to occur in several locations and that it is much more highly localised than infiltration-inflow. In the top 10% of highest predicted likelihood values on a relative scale, infiltration-inflow affects 2.9% and stream and spring capture affects just 0.2% of the combined sewers by length, and several sewers predicted to have low likelihood of infiltration-inflow have high likelihood of stream and spring capture; this may have implications for the way in which water companies prioritise sewer condition surveys in future. The second purpose of this is therefore to present a useful scoping tool that could be applied by water companies to use limited data to probabilistically identify sites for further investigation by more resource-intensive techniques to confirm or eliminate stream and spring capture. The model is robustly evaluated using several validation data sources, suggesting that it performs well. In particular, at 60 selected sewers the model consistently differentiated higher and lower capture likelihoods where, on review of evidence on a site-by-site basis, a water company would wish or would not wish (respectively) to undertake further field tests to confirm or rule out capture in sewers in that vicinity. Infiltration-inflow was validated successfully against CCTV survey data for over 12,000 sewers in the network, and the predicted probabilities of infiltration-inflow being present are significantly higher at sites where infiltration-inflow has been observed than at sites where it has not been observed.

The overall conclusion from this thesis is that stream and spring capture does occur in combined sewer networks and that the water industry should now apply the methods and tools across the UK. Knowledge derived from the case study of Sheffield can be applied to other areas in the UK, and indeed elsewhere in the world, in combined sewer areas. It has shown that, while not easy to confidently identify where this occurs, it does happen and that the next stage should be to quantify the contribution to combined sewers in order to evaluate the costs and benefits of separating these “lost” clean waters from the sewer system.

Acknowledgments

This PhD was funded by a Departmental Studentship from the Department of Civil and Structural Engineering, University of Sheffield. I would like to sincerely thank Prof. David Lerner and Dr Rachel Horn for supervisory support throughout the thesis, for asking tough questions and providing advice and guidance. I have learnt a lot.

This study has been possible with support in data and in kind from Yorkshire Water – notably Deborah Redfearn, James Kitson, Sarah Gledhill, David Rose, Stuart Little and Richard Kidd – for access to sewer network data, supply of resources, permission to access the sewer network for sampling, and permission to publish material relating to this.

Specific thanks go to Prof. Adrian Saul of the Pennine Water Group (University of Sheffield) for his advice and input on the project and for feedback on the literature review; Markus Antener of ERZ (Entsorgung + Recycling Zürich) for use of maps and images and for verifying facts relating to the Zurich Stream Concept; Dr Andrew Phillips for GIS support and advice throughout; Gavin Sailor for data support and advice on sewer networks; Dr Will Shepherd for his time, advice and guidance on many research issues throughout; Andrew Fairburn, Dr Steve Thornton, and staff from the Pennine Water Group Labs for support with the laboratory work and fieldwork; Paul Fidler from Drains Aid for assistance at untimely hours of the day and night throughout the sewer sampling program; Dr Vikas Kumar of Rovira i Virgili University, Catalonia, for guidance in Bayesian Belief Networks and technical support with the modelling and Netica software; Richard Allitt, Graham Squibbs, Jamie Margetts, John Blanksby, Steve Wragg, Will Shepherd, John Malone, Peter Skipworth for contributing their time and expertise to the Bayesian Belief Network modelling; John Malone and colleagues at Clear Ltd for data and feedback on modelling results.

Thanks to all my colleagues past and present in the Catchment Science Centre, Groundwater Protection and Restoration Group, and Pennine Water Group, for making it such a pleasant, stimulating and supportive place to work for the last few years.

Finally, I thank my family for their support, and my wife, who kept me going and without whom I surely would never have finished.

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Nomenclature

BBN – Bayesian Belief Network

BGS – British Geological Survey

COD – chemical oxygen demand

CPT – conditional probability table

CSO – combined sewer overflow

DEM – digital elevation model

DRN – Detailed River Network map product

DTM – digital terrain model

EA – Environment Agency

GIS – Geographical Information System

LiDAR – Light Detection and Ranging (topographic data)

OS – Ordnance Survey

SuDS – Sustainable Drainage Systems

TSS – total suspended solids

UKWIR – UK Water Industry Research

WFD – Water Framework Directive

WwTW – wastewater treatment works

1 Introduction

1.1 A lost river captured into combined sewers

Far down from the thunder
And rush of the street,
Flow Westbourne and Tyebourne
And Effra and Fleet,
'Neath blue skies and grey skies
Once freely that ran -
Lost rivers of London,
Forgotten of man.
The Lost Rivers – Cicely Fox Smith, 1931

Among London's many lost rivers was the River Fleet. Fed from natural springs on Hampstead Heath and augmented by baseflow from ancient wells and minor tributaries, it flowed southwards to meet the River Thames at the modern-day Blackfriars Bridge. The story of how it has become buried and lost, from sight though not from memory, serves to introduce the context and motivations for this thesis.

Over its history, the River Fleet has gone by many names. Its name is derived from the Anglo-Saxon *fleotan*, referring to a place where boats and barges can float (Foord 1910). This reflected its use as a tidal creek dock at the point where it met the Thames, and was navigable by boats or barges throughout the Middle Ages. It has also been known as Holebourne and River of Wells. In the case of the former, the name is imprinted on the area now known as Holborn – "bourne" or "burn" meaning a spring-fed stream (Foord 1910). In the case of the latter, the name reflected the many wells dug into the alluvial gravels, such as the Clerks' Well on a tributary of the Fleet, and St Bride's Well (Ashton 1889).

Much has been written of the River Fleet and its tributaries over time, providing clues as to its gradual decline as a watercourse and eventual conversion into a sewer. But while many have charted its history and route under modern-day London (Barton 1992, Bolton 2011, Myers 2012, Talling 2011), few have considered what has actually happened to the waters. This lost river is not just culverted, but "captured" into the combined sewer system.

Early accounts indicate its clean waters provided drinking supplies during the time of William the Conqueror (Ashton 1889, Lethaby 1902). The development of early sewers since the Roman times, including in London, focused on draining rainwater rather than foul water (Butler and Davies 2011, Myers 2012). Human waste was disposed of in cesspits, which leaked into the gravels beneath the city, contaminating wells, springs and watercourses including the River Fleet (Barton 1992, Butler and Davies 2011). Despite legal provisions that designated the Fleet as a sewer for rainwater only, there is no doubt that like many watercourses in rapidly urbanising areas all over the world, the river became polluted by effluent from houses and industries of the expanding city over the centuries (Barton 1992).

In response to the pollution and increasing urbanisation, the Fleet was bridged in many places, particularly in the lower reaches, and buildings started to turn their backs on the watercourse (Howell 1657). By the 1700s, it was known as the Fleet Ditch and famed for its dangerously polluted state as an open sewer. It is described in Alexander Pope's satirical poem *The Dunciad II* in 1728:

> "To where Fleet-ditch with disemboguing streams
>
> Rolls the large tribute of dead dogs to Thames
>
> The king of dykes! than whom no sluice of mud
>
> with deeper sable blots the silver flood."

The situation worsened by the 19th century: "…a most offensive and open drain or part of the Fleet Ditch passes by the back of the houses and [runs] under West Street where it disappears….The evils from this open sewer are of course most felt in summer when the stench is intolerable" (Metropolitan Working Classes' Association for Improving the Public Health 1847).

All across London, the existing sanitation and drainage system was buckling under the pressure of the growing population, with open sewers like the Fleet discharging waste that stagnated in the tidal River Thames. Two important events marked a new paradigm and sealed the fate of the Fleet and rivers like it. One was the Broad Street cholera outbreak in 1854, where physician John Snow proved the link between contaminated water and disease for the first time. The second was the infamous Great Stink during the summer of 1858, where the smell of sewage in the River Thames was severe enough to suspend Parliament (**Figure 1**).

Figure 1 *The Silent Highwayman: Death rows on the Thames, claiming the lives of victims who have not paid to have the river cleaned up, during the Great Stink* by John Leech, cartoon published in Punch Magazine, 10 July 1858.

The Fleet was also known to flood, such as around present day St Pancras. To tame its flows, enable urban development, and sanitise it by masking away the sight and smells to reduce waterborne disease, the river was extensively buried underground in culverts. The last remaining open sections flowed through Hampstead until they too were swallowed up by the suburban development in the 1870s (Talling 2011). The Fleet's many ancient springs were similarly covered over by urban development. Black Mary's Hole was an ancient spring draining to the Fleet near Clerkenwell; it was buried beneath houses in Spring Place and converted into a cesspit, remaining hidden and polluted until years later in 1826 it was rediscovered when it re-emerged causing a footpath to collapse (Ashton 1889).

In 1859, the Metropolitan Board of Works commissioned the development of London's combined sewer system designed by Joseph Bazalgette, which would form the blueprint for modern sewerage around the world. To alleviate the stench from the tidal Thames and tributaries stagnating with sewage, new interceptor sewers would divert wastewater and rainwater eastwards along a shallow gradient to meet the Thames further downstream beyond the city. Earlier proposals by Edwin Chadwick to construct a separate sewer system, with separate pipes for wastewater and for rainwater, were rejected due to costs (Butler and Davies 2011). A combined sewer system instead conveys wastewater and rainwater together in a single pipe, and is still used in many cities across the world today.

The River Fleet and many other lost rivers of London including the Westbourne, Tyburn, Effra and Walbrook, were permanently written off as watercourses at this point, having already become sewers in practice. Occupying ideal ground topographically, they were formally piped and adopted as combined sewers, rather than being restored by diverting all wastewaters to new sewer pipes. Indeed, Bazalgette's calculations for sizing the interceptor sewers included not only rainwater from the contributing catchment area and estimates of wastewater per head of population, but also the baseflow from the Fleet and other lost rivers (Myers 2012).

Today, the River Fleet is a combined sewer; its spring-fed streamwater is diverted into Victorian high-level, mid-level and low-level interceptor sewers, joining with the capital's sewage to reach the wastewater treatment works (WwTW) some 14 km to the east. Its original streambed is a brick-lined sewer below the streets of Holborn, its flows only reaching the Thames as a combined sewer overflow (CSO) (**Figure 2**).

There is an enduring fascination with lost rivers. They are immortalised in fiction and non-fiction, and reflected in the names and locations along their former routes. They are popular with urban explorers who document and photograph their walks through culverts, drains and sewers. There are walks and talks that inspire public fascination about what lies beneath their feet, and sometimes the lost rivers are seen when they flood after heavy rainfall, such as when London's lost River Effra flooded in Herne Hill in 2007 (Talling 2011).

We know that in many cities around the world, rivers of similar sizes to the Fleet continue to flow in culverts but not as part of the combined sewer system. The River Fleet was probably the largest of London's lost rivers, approximately 90 m wide at the point where it met the River Thames (Myers 2012), but its upper and middle reaches, as well as the entirety of many of London's other lost rivers, may be more appropriately considered streams or brooks. The conversion of the Fleet itself into a combined sewer may be exceptional considering its size, but what has become of the many small tributaries and springs that contributed flow to the Fleet and other lost rivers like it? They too appear to have been captured completely into the combined sewers, because there are no surface watercourses visible in the catchment areas, and there are no culverted watercourse outfalls visible to the River Thames. In towns and cities around the world, have lost streams and springs – though not necessarily larger rivers – shared a similar fate to the lost River Fleet?

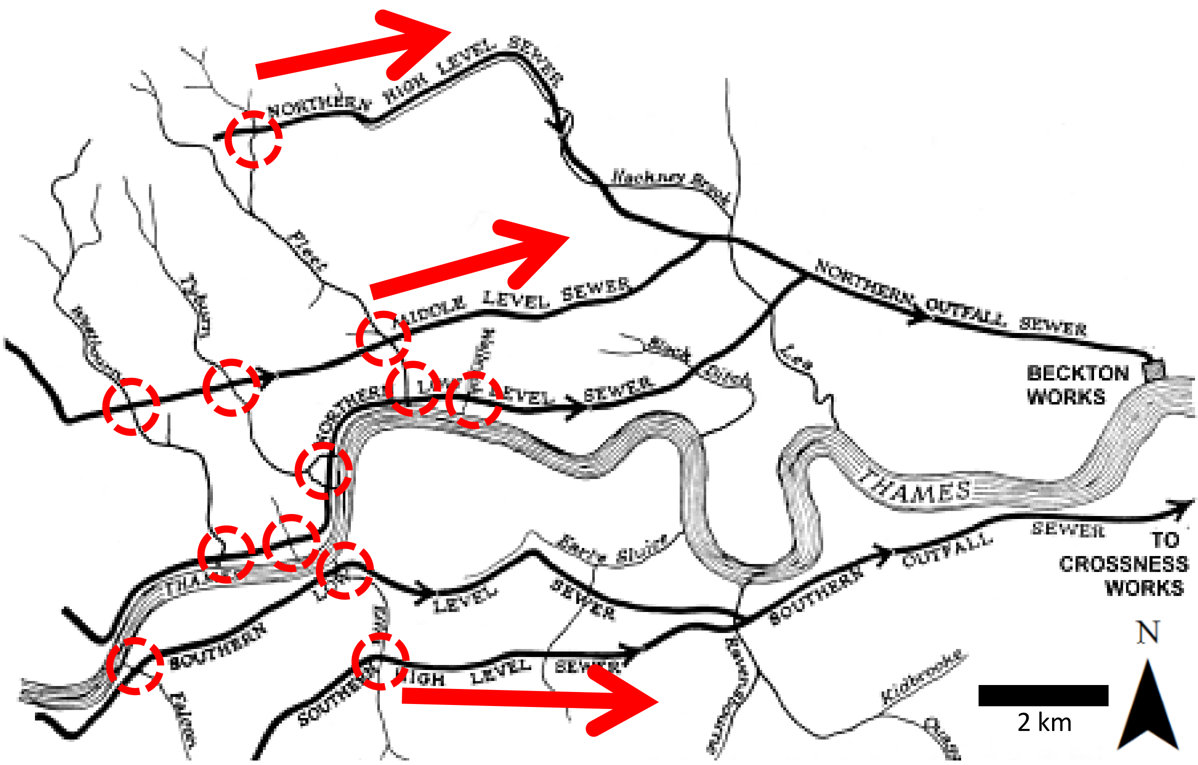


Figure 2 Lost rivers of London; the Fleet, Walbrook, Tyburn, Westbourne, Effra and Falcon Brook are all captured into interceptor sewers at points marked by red circles. The original beds of these lost rivers are now combined sewers, only flowing to the River Thames as combined sewer overflows. Some, like the Hackney Brook, River Lea, and Ravensbourne are not captured and flow – albeit culverted in many places – to the River Thames. (Image: http://www.turtleshellprod.com/media-uploads/sewers.gif).

1.2 Considerations of lost rivers and capture

This thesis is concerned with lost rivers, streams and springs that have, like the Fleet, been not just buried into culverts, but converted, diverted or otherwise captured into combined sewer systems. This can be considered from a river restoration perspective or from a sewerage management perspective. These separate viewpoints frame the issue with different motives and legal drivers, which are now discussed further to set the context for the aims and objectives of this thesis.

1.2.1 Watercourses and river restoration

Lost rivers are a symptom of the urban stream syndrome by which urban watercourses around the world have been polluted, modified and neglected (Walsh et al. 2005). Urbanisation has led to widespread degradation in watercourses, with fields of research developed around identifying the impacts on chemical and physical water quality, on the ecological functioning of related aquatic and terrestrial habitats, on the flood risk associated with altered channel and urban catchment hydrology, as well as on the social impacts of amenity, well-being and public health (e.g. Everard and Moggridge 2012, Findlay and Taylor 2006, Paul and Meyer 2001, Walsh et al. 2005, Wenger et al. 2009). There is also considerable interest in the academic literature in support of science and policy of managing urban watercourses (e.g. Bernhardt and Palmer 2007, Bernhardt et al. 2005, Booth et al. 2004, Palmer et al. 2007).

Specifically, work isolating the impacts of culverts or burial of streams has shown that culverts reduce both in-channel and riparian habitat connectivity, with impacts for water quality, fish passage and flood risk (e.g. Balkham et al. 2010, Bernet 2010, Kaushal et al. 2008). There is a developing body of science and practice in the restoration of degraded urban watercourses, including the daylighting (also known as deculverting) of buried watercourses (Broadhead and Lerner 2013, Wild et al. 2011). There are examples around the world of restoring buried sections of watercourse – often short reaches at a time – for multiple environmental, social and economic benefits (e.g. Buchholz and Younos 2007, Nolan and Guthrie 1998, Pinkham 2000, Sinclair 2012). Environmental benefits include reversing the aforementioned impacts of culverts on the water quality and habitats. In the UK and EU, daylighting is recognised as a mitigation measure for physically modified water bodies under the Water Framework Directive (WFD, 2000/60/EC), and has featured in planning policies in the UK and North America (CIWEM 2007, Environment Agency 1999, EPA Office of Wetlands Oceans and Watersheds 2010, Federal Interagency Stream Restoration Working Group 1998, SEPA 2006). Flood risk also forms a key motive behind restoring buried urban streams (Wild et al. 2011).

Such restoration is constrained by many factors. First, competing requirements for urban space mean that other infrastructure occupying land over culverted watercourses can take priority. Second, the costs of such work are often substantial, though the cost-benefit can become favourable when all factors such as flood risk, costs of repairing or replacing ageing culverts, or the lost opportunities for attractive waterfront regeneration are taken into account (Pinkham 2000). To move beyond daylighting buried watercourses being a piecemeal and opportunistic undertaking, a long term planning strategy is needed that ties into multiple stakeholder interests and identifies opportunities to daylight buried watercourses along with redevelopment (Broadhead and Lerner 2013). One such strategy in the UK, the *London Rivers Action Plan* (Mayor of London 2009), proposed the daylighting of the city's culverted watercourses but did not consider the implications of truly lost streams and springs that have been captured into the combined sewer system.

The legal responsibilities for culverts in England and Wales remain with the landowner, who sometimes may not even be aware of a watercourse flowing beneath their property (Environment Agency 2014). In towns and cities, watercourses of all sizes may have been culverted. Under the Land Drainage Act (1991), the local authority or internal drainage board have responsibilities and rights related to the management and drainage of smaller "ordinary watercourse". Larger watercourses are designated "main river", and come under the responsibility of the Environment Agency in England, Natural Resources Wales or SEPA (Scottish Environmental Protection Agency). Any works to newly culvert a watercourse or daylight an existing culvert require consent by the relevant authorities and assessment of impacts under the WFD. In urban areas, complex land ownership and multiple authorities and stakeholders can raise challenging ownership and liability issues (Pinkham 2000).

Despite some speculative suggestions over the years for restoring and daylighting the lost River Fleet through London (Myers 2012), captured watercourses have rarely been considered explicitly through the river restoration perspective. Indeed, if like the Fleet, the watercourse is now a combined sewer through capture, restoration is made all the more complex. The captured watercourse may also no longer be considered a watercourse at all under legal definitions in the UK; if it flows into a sewer it may have been designated as part of the sewer system and so falls under the water company's responsibility. From this point of view, stream and spring capture represents an additional degradation of urban watercourses, over and above the many impacts of culverting. There is a key driver from this perspective to restore lost watercourses, potentially including captured watercourses, as natural functioning water bodies again, for environmental, social and economic benefits. This raises a number of important questions from a river restoration perspective:

- How many streams and springs have been lost and captured into combined sewer systems?
- What are the resultant environmental impacts of lost streams and springs on remaining natural watercourses?
- What are the technical challenges associated with restoring watercourses that have not only been culverted, but converted into sewers, and is it possible to find space in urban areas to restore them as true natural watercourses?
- Does the current legal and policy background enable lost and captured streams and springs to be restored, and who should do this?

1.2.2 Sewer systems

From the viewpoint of a water company and the water industry, captured streams and springs are primarily a question of design and operation of sewer systems. Sewer system management has key drivers around sustainability (of economics, water resources and carbon emissions) and reducing impacts on the environment and on the public (e.g. Kelda Group 2011). The impacts of captured water can be considered with regard to two key aspects of sewer systems.

One consideration is wet weather flow management. Combined sewers convey both wastewater and rainwater in the same pipes to the WwTW. If watercourses have been captured into combined sewers, then they may be contributing to elevated stormwater in the pipes because the rainwater associated with those former river networks is flowing into the sewers and not reaching downstream river networks. Capacity for stormwater in combined sewers is a major focus area for the water industry. Insufficient capacity causes sewers to flood, either into properties or in a controlled and consented way via combined sewer overflow (CSO) spills to river networks, affecting water quality and the environment (Brownbill et al. 1992, Butler and Davies 2011, Metcalf and Eddy Inc. et al. 2004). Urban stormwater flooding – this is the flooding associated primarily with pluvial water being unable to drain effectively away from the surface, and so not yet mixed with wastewater in combined sewers – is also of interest due to its costly impacts. There have been recent moves across the water industry towards separation of rainwater from combined sewers, either by installation of separate surface water pipes or by soft-engineering solutions such as disconnection of downpipes and local infiltration basins (Hurley et al. 2008, United States Environmental Protection Agency 1999). In urban planning, use of green infrastructure and sustainable drainage schemes (SuDS) can reduce or slow the runoff entering the combined sewer system, reducing CSO spills, sewer flooding and surface water flooding whilst bringing a range of additional environmental or ecosystem services benefits (ALCOSAN 2012, Burian et al. 1999, EPA Office of Wetlands Oceans and Watersheds 2010, Thames Water 2009, Thomas and Crawford 2011, UKWIR 2009, Woods-Ballard et al. 2007). Stormwater management is an issue with numerous stakeholders relating to the water industry: water companies, local planning authorities, flood risk managers, environmental regulators, and the wider public. Where watercourses have been captured into combined sewer systems, they may be highly relevant to stormwater management because they stand to exacerbate the problems associated with lack of combined sewer capacity. One current example is the Counters Creek sewer in London, which appears to have been the route of a lost stream of the same name and along which sewer flooding and poor surface water drainage has arisen due to a lack of sewer capacity. Proposed management measures include a £32 million stormwater relief sewer as well as localised retrofitting of SuDS, but nowhere in the literature is there explicit consideration of disconnecting the captured watercourse from the sewer system (Thames Water 2009).

The second consideration is that captured streams and springs contribute a constant clean extraneous baseflow to combined sewer systems. In this manner, they are similar to infiltration-inflow, which is an ongoing key concern to water companies (Ellis 2001). Infiltration-inflow has been the focus of numerous studies that consider how to detect, quantify, predict and manage it (UKWIR 2012). Definitions of infiltration-inflow do not explicitly consider captured streams and springs; they focus instead on the intrusion of groundwater through pipe cracks and defective joints, and direct inflows through unintentional cross-connections or flooded watercourses, or inappropriate discharge of clean coolant waters to combined sewers (Butler and Davies 2011, Metcalf and Eddy Inc. et al. 2004). A reconsideration of the definitions of infiltration-inflow is required to ensure that captured streams and springs are included. Methods to rehabilitate sewers primarily focus on waterproofing the pipe (Read 2004); this might fail to address elevated clean baseflow in all cases where streams and springs have been captured.

Captured streams and springs, like the lost River Fleet, may still flow in combined sewers from the clean spring-fed baseflow associated with the old watercourse. That clean baseflow contributes a constant loading to the WwTW that must be managed, just as with infiltration-inflow. This study provides the first explicit consideration of stream and spring capture, and establishing the presence and impacts of the clean baseflow component will provide a useful contribution to the water industry and state of knowledge on the sustainable management of combined sewer systems. Given the existing research and investment into managing infiltration-inflow in combined sewer networks around the world, there is a strong case to consider whether captured streams and springs are worthy of attention by water companies. There are key questions from this perspective:

- How common is stream and spring capture?
- How does stream and spring capture occur?
- Where does stream and spring capture occur, and what methods are available to identify it?
- Is it distinctly different from infiltration-inflow, and is it adequately considered by the water industry at the moment?
- How much water from captured streams and springs is flowing in combined sewers and reaches WwTWs?
- What are the costs and consequences of capture for the design and operation of combined sewer networks?
- What options are there to manage capture?

1.3 Thesis objectives

Before any management options such as stream restoration can be explored, stream and spring capture must first of all be understood from the perspective of the water industry, as a potential problem facing combined sewer networks. The overall aim of the thesis is to demonstrate that streams and springs have been captured into combined sewer systems, and to develop methods to identify where it happens. Four main objectives have been set:

1. **To establish the existing state of knowledge on stream and spring capture.** There has not yet been a comprehensive review of the academic or applied literature focusing explicitly on stream and spring capture as a distinct issue separate to infiltration-inflow. Important research questions to answer are: what evidence is there that stream and spring capture occurs, what are the costs and consequences for the water industry, how can it be detected, and what experience has there been of managing it?
2. **To develop and apply a methodology to indicate where streams and springs have been captured into the combined sewer system.** Identifying where streams and springs have been captured is a vital first step before any meaningful questions about the specific local costs or management opportunities can be explored. Important research questions to consider are: what evidence is available to indicate where capture occurs, how can this evidence be used and what uncertainties are associated with it, and how many streams and springs have been captured in an example case study catchment?
3. **To develop and apply a new water typing technique to detect stream and spring capture.** There is a need for a direct method to detect captured streams and springs in a combined sewer and no methods yet have specifically focused on this issue. Techniques available to detect infiltration-inflow may present a number of limitations when applied to stream and spring capture. The use of major and minor ion water typing, well established in hydrogeology fields, has not been applied to either infiltration-inflow or stream and spring capture. The primary research question is whether or not major and minor ion water typing techniques are able to detect capture.
4. **To develop and apply a predictive Bayesian Belief Network (BBN) model to compare the likelihood of stream and spring capture to infiltration-inflow across a combined sewer network.** It would be of benefit to the water industry to develop a model that is able to predict the presence of stream and spring capture in combined sewers, and to enable comparison to infiltration-inflow. This builds on the work developed throughout the thesis, integrating the lines of evidence for scoping the likelihood of capture across a combined sewer network to target sewers for further

investigation. A BBN modelling approach is presented because of its strengths in data poor applications, its ability to incorporate expert knowledge directly, and its explicit inclusion of uncertainty in model outputs. The BBN will be developed using a real case study sewer network, enabling both site-specific and general research questions to be addressed: what is the predictive accuracy of the model, what is the state of expert knowledge on predicting stream and spring capture and how does this compare to infiltration-inflow, and how does the relative likelihood of stream and spring capture compare with infiltration-inflow?

1.4 Thesis structure and statement of author contributions

This thesis is structured around the research objectives. Each chapter builds on the knowledge from the previous chapters, and they are presented with their own introductions, literature reviews and interim conclusions. It is the intention that the separate chapters will be submitted for publication in academic journals, in either an abridged or complete form.

Chapter 2 presents a thorough review of the academic and grey literature on the evidence of stream and spring capture, its consequences and costs, and opportunities for management. The research was conducted by the author (Broadhead) under the academic supervision of Horn and Lerner. The analysis of costs of stream and spring capture based on a proxy of domestic wastewater charging was originally developed by Lerner, then recalculated by the author. The chapter has been submitted and published as:

> Broadhead, A.T., Horn, R. and Lerner, D.N. (2013) 'Captured streams and springs in combined sewers: A review of the evidence, consequences and opportunities'. Water Research 47(13), 4752-4766.

Chapter 3 then explores evidence and methods that can be used to identify where stream and spring capture is likely to occur, using an approach of multiple lines of evidence. This is applied to a case study of Sheffield, UK. This research was conducted by the author (Broadhead) under the academic supervision of Horn and Lerner. An abridged form of this chapter was published as a technical note in the Sewer Processes and Networks Conference held in Sheffield in August 2013:

Broadhead, A.T., Horn, R. and Lerner, D.N. (2013) 'A multiple lines of evidence approach to indicate capture of lost urban streams and springs in combined sewers'. 7th International Conference on Sewer Processes and Networks, Sheffield, UK, 28-30 August 2013.

In Chapter 4, a method is developed to detect the presence of captured streams and springs in combined sewers, using a chemistry-based water-typing method. The fieldwork sampling program was designed and undertaken by the author (Broadhead). For logistical and health and safety reasons, the author was supported to access and sample from the sewer network by Yorkshire Water through the contractor Drains Aid. Laboratory analysis was conducted by the author (Broadhead) with technical support from Andrew Fairburn and Steve Thornton (GPRG, University of Sheffield). The interpretation and analysis was conducted by the author (Broadhead) under the academic supervision of Horn and Lerner. This chapter is being prepared for submission.

Chapter 5 develops and applies a BBN model to the Sheffield case study to predict the likelihood of stream and spring capture and infiltration-inflow across a combined sewer network. This model substantially builds on the BBN developed as part of a UK Water Industry Research (UKWIR) project predicting infiltration-inflow risk to combined sewers, to which the author (Broadhead) contributed (UKWIR 2012). This BBN uses expert knowledge to parameterise the model, and the contributions of experts from across academia and the water industry are gratefully acknowledged. The author was responsible, under the academic supervision of Horn and Lerner, for the design and implementation of the expert workshops, the development of the BBN model, the preparation and analysis of input data for the model, and the analysis of the model results. Dr Vikas Kumar provided both general advice on BBN development as well as conducting some specific tasks. These involved processing of expert questionnaire data using a *compatible and critical probability* method based in Matlab scripts – devised by himself and published previously (Kumar et al. 2013) – and processing of some of the model sensitivity analysis in the latest version of Netica software. This chapter is being prepared for submission.

Chapter 6 is the thesis conclusion, which synthesises the results of the technical chapters to specifically answer the research questions of the thesis, consider the wider policy questions raised about stream and spring capture, and make recommendations for further research. This is the work of the author (Broadhead) with academic supervision from Horn and Lerner.

2 Captured streams and springs in combined sewers: a review of the evidence, consequences and opportunities

2.1 Introduction

Steady intrusion of extraneous waters to combined sewer systems is an increasingly important issue facing water infrastructure around the world (Ellis 2001). This intrusion is commonly considered in the literature to be the unintentional ingress of clean groundwater through pipe cracks and joints, where the sewer invert lies fully or partially below the water table (UKWIR 2012). This increases the dry weather baseflow, so reducing pipe capacity for stormwater flows and increasing the likelihood of surcharging and combined sewer overflow (CSO) spills, as well as increasing pumping and treatment costs at wastewater treatment works (WwTWs) (Butler and Davies 2011, Ellis 2001, Metcalf and Eddy Inc. et al. 2004). It can also contribute sediment and debris to the system, giving rise to blockage (ALCOSAN 2012, Ellis 2001). There is awareness in the water industry that groundwater infiltration-inflow to combined sewers has serious implications for operational efficiency, environmental quality (especially with increased sewer flooding risk) and sustainability drivers (including energy costs and a UK water industry carbon reduction commitment), and that there are techniques available to detect and tackle it (UKWIR 2012). It particularly affects ageing and degraded combined sewers.

Another source of intruding extraneous water is the deliberate capture of streams and springs to combined sewer systems. This has a similar effect to general groundwater infiltration-inflow by increasing clean baseflow (**Figure 3**), but represents a different mode of entry with unique challenges in identifying and managing it. It is also distinct from the burial of streams conveying storm drainage in separate sewer networks; these do not get captured to WwTWs. The UK water industry recognises the principle that captured streams and springs are contributing flow to combined sewer systems. However, there has not been an explicit discussion of the issue in the published literature or any known attempts to quantify or manage it. Stream capture is also related to interests in the ecological status of watercourses heavily modified by culverting, under the European Water Framework Directive (2000/60/EC).

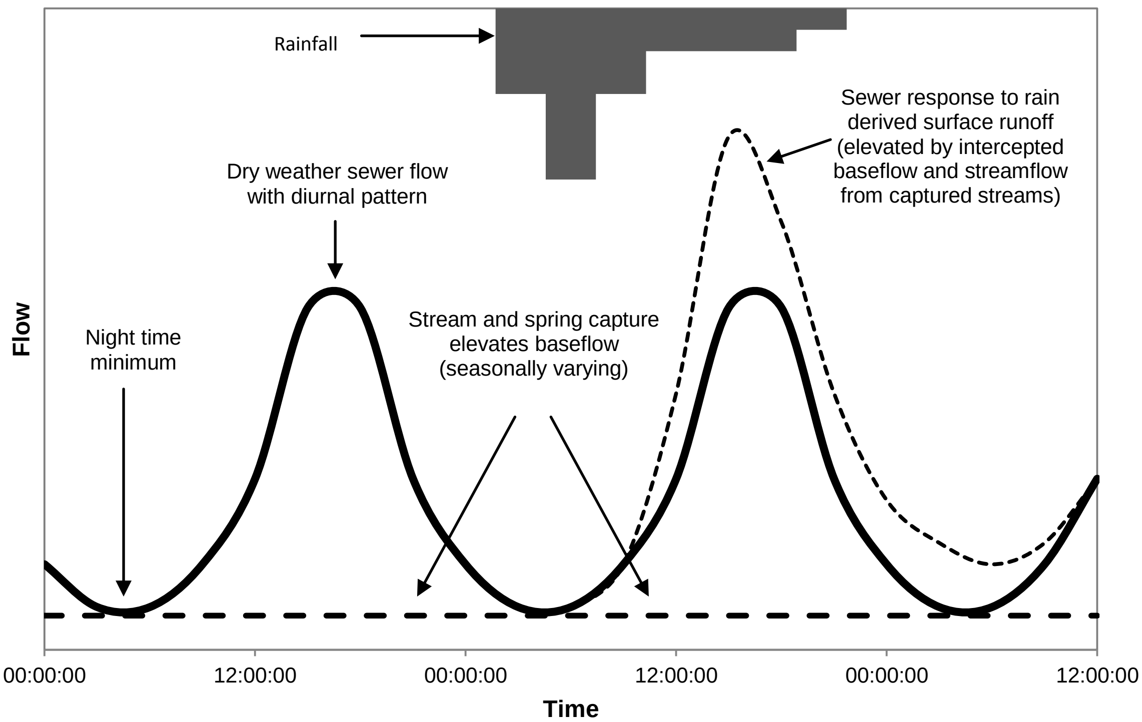


Figure 3 Idealised unit hydrograph of combined sewer flow and the effects of captured streams and springs on baseflow and surface runoff response.

A review for the UK water industry found many studies that have sought to map, quantify and model (physically and empirically) infiltration-inflow to sewers (UKWIR 2012), and water companies are investing to reduce this source of clean baseflow with sewer rehabilitation. It is therefore important that captured streams and springs are understood and considered as a component of steady intrusion of extraneous water to combined sewer networks. The aim of this chapter is to present a review of the evidence and case studies on captured streams and springs in combined sewers, to answer the following key questions for the water industry:

- What is the evidence that streams and springs have been captured into combined sewer systems?
- How does stream and spring capture occur, and why?
- How can captured streams and springs be identified in combined sewers?
- How much water do captured streams and springs contribute to combined sewers?
- What are the consequences and costs of captured streams and springs?

- What are the management options available, and has this been attempted elsewhere?

2.2 Method

A thorough search identified peer-reviewed academic papers and grey literature detailing any evidence or international case studies of captured streams and springs in combined sewers. Absence of consistent terminology reflects the lack of explicit published discussion of this issue, especially in the UK; **Table 1** summarises this and defines the key terms used in this thesis. Multiple search terms were therefore used for captured streams and springs, and with so few relevant results obtained, the wider literature on infiltration-inflow was reviewed to identify further references that explicitly refer to stream and spring capture within their focus on groundwater infiltration through cracks and joints.

Research (some peer-reviewed) on infiltration-inflow acknowledges the principles of stream and spring water in combined sewers in general terms (e.g. Franz 2007, Uibrig et al. 2002, UKWIR 2012), but no peer-reviewed papers have specifically considered this issue. References to literature from the 1980s were found that acknowledge the capture of streams and springs, but it was not possible to access the original texts (Klass 1985 and Pfeiff 1989, in S & P Consult 2008). Grey literature dominates the review. Case studies are summarised in **Table 2**, with the most detailed examples from Pittsburgh, San Francisco and Zurich. Very little information has been found on captured streams and springs in UK combined sewers, although there are numerous publications on lost rivers in culverts (Barton 1992, Bolton 2011, Talling 2011).

Table 1 Overview of key terminology used. For clarity, all other related terms in known usage (published and unpublished) are also listed.

Term	Definition	Other terms in literature or industry usage
Culverting	Artificial encasement of a stream or spring in a pipe or tunnel below the ground for part or all of its length.	Stream burial. NB: culverted streams may act as storm sewers as part of the surface water drainage in a separate sewer system, which is distinct from the capture into combined sewers.
Extraneous water	Steady intrusion of all clean waters (including groundwater infiltration-inflow and stream and spring capture, but not surface runoff) into combined sewers.	Extraneous clean water; infiltration-inflow; parasite flow; unaccounted for flow.
Infiltration-inflow	Unintentional ingress of groundwater through pipe cracks and defective joints, contributing clean baseflow to combined sewers.	Extraneous clean water; infiltration-inflow; parasite flow; sewer leakage; steady groundwater intrusion; unaccounted for flow. NB: some of these terms implicitly include clean baseflow from stream and spring capture.
Sewer inflows	Unrelated problem of unintentional ingress of groundwater or rainfall runoff to separate foul sewers, defined here for clarity.	Extraneous clean water; illicit connections; infiltration-inflow; parasite water; unaccounted for flow.
Stream and spring capture	Deliberate direct connection of streams and springs to combined sewers, with unintended consequences of increased clean baseflow.	Extraneous clean water; direct stream inflows; infiltration-inflow; misconnected surface waters; parasite flow; unaccounted for flow.

Table 2 Case studies reporting captured streams and springs in sewers. Evaluation of the evidence indicates whether they contribute flow to WwTWs; some literature refers to culverted watercourses acting as storm sewers. Only Pittsburgh, San Francisco and Zurich case studies provide substantial detail.

Case study	Is stream/spring captured and does it flow to WwTW? Summary of supporting evidence	Source
Pittsburgh, USA	**Yes** – Report from water authority details connected streams to combined sewers, with estimated baseflows for each. Separation planned, some completed.	(ALCOSAN 2012, Pinkham 2001, Schombert 2006, Troianos et al. 2008, US Army Corps of Engineers 2009).
San Francisco, USA (Islais Creek and others)	**Yes** – Report from water authority details connected streams to combined sewers. Fully mapped, with indication that most are perennially spring-fed, and some ephemeral. Separation planned.	(City and County of San Francisco 2010, Griffith 2006, Jencks and Leonardson 2004, Smith 2007a, Smith 2007b).
Seattle, USA (Ravenna Creek and others)	**Yes** – Stated connection to combined sewers, but undetailed. Separation planned.	(City and County of San Francisco 2010, Smith 2007a).
Portland, USA	**Yes** – Stated connection to combined sewers, but undetailed. Separation planned.	(City and County of San Francisco 2010, Smith 2007a).
Detroit, USA (Bloody Run Creek)	**Unlikely (just culverted)** – Article suggests daylighting could separate large volumes from sewer system, but likely refers to the diversion of storm runoff rather than captured flow. Culverted stream is storm sewer, but not flowing to combined sewers or WwTW.	(Bienkowski 2011).
Cincinnati, USA (Lick Run)	**Unlikely (just culverted)** – Report details conversion of Lick Run to sewer, but now is a storm sewer and not flowing directly to combined sewers or WwTWs. Some captured stream flow a possible component in combined sewers, but not detailed.	(Metropolitan Sewer District of Greater Cincinnati 2012).
Philadelphia, USA	**Possible** – Stated stream conversion to sewers, but unclear whether still flowing to WwTWs. Culverted streams could be separate storm drains or diverted to interceptor sewers.	(Levine 2008).
New York, USA	**Possible** – Reports, maps and photographic evidence of stream conversion to sewers, but unclear whether still flowing to WwTWs. Culverted streams could be separate storm drains or diverted to interceptor sewers.	(Duncan 2011a, 2012, Duncan and Barry 2010, Duncan and Head 2010).
Toronto, Canada (Garrison Creek and others)	**Yes** – Reports, maps and photographic evidence of stream conversion to combined sewers. Suggested that some culverted streams partly used for separate stormwater drainage and CSO spills, but baseflow intercepted to WwTWs.	(Cook 2011).
Prague, Czech Republic	**Yes** – Stated connection of streams to combined sewers, but undetailed.	(Bareš et al. 2012).
Zurich, Switzerland	**Yes** – Report and maps from water authority details connection and conversion of streams and springs to combined sewers. Discusses impact on WwTW. Major separation project completed by daylighting streams.	(Antener 2012, City and County of San Francisco 2010, Conradin and Buchli 2005, ERZ 2000, 2007, Herrmann 1990, Mühlethaler 2011, Pinkham 2000, Smith 2007a).
Bamberg, Germany	**Yes** – Stated conversion and connection of streams to combined sewers, but undetailed. Discusses impact on WwTW. Separation planned.	(Unknown 2009).

Emscher River, Germany	**Unusual –** Widely considered a captured watercourse. Historically used as an open combined sewage canal for industrial and domestic wastewaters in the region, because unstable ground precluded conventional sewer network. Flows treated at a WwTW prior to confluence with the Rhine. Full separation underway with new deep combined sewer beneath river receiving all wastewaters; river undergoing renaturalisation.	(Londong and Becker 1994, Schulz 2012, Teichgräber and Hermanns 1996)
Brussels, Belgium (Senne)	**Unusual –** Widely considered a captured river, but included here for clarification. Converted from historical stream to open sewer then covered and rerouted as trunk combined sewer, receiving all Brussels wastewaters without treatment until 2007. Since then, new WwTWs and interceptor combined sewers separate most sewage before entering the river.	(Anon. 1999, Aquaris 2014, Garnier et al. 2013, Le et al. 2014, Solvel 2014).
Paris, France (Bièvre)	**Yes –** Stated conversion of Bièvre from historical stream to open sewer then covered as trunk combined sewer. Channel to the Seine is now a CSO; baseflow continues to left bank collector sewer to WwTW. Some open clean sections remain upstream. No details on impacts of the capture on wastewater system. Some sections of city have been daylighted – unclear how this has been separated from wastewater.	(APUR 2001, Gandy 1999, IAURIF 2003, Simpson 2005).
Beverley, UK (Pasture Terrace)	**Yes** – Reactivated spring-fed a stream observed to drain with stormwater to combined sewer causing flooding.	(Ewen 2012).
London, UK (River Fleet and others)	**Possible** – Stated conversion of many streams to combined sewers. Some captured into the interceptors sewers along their route, with only storm overflows reaching the River Thames (e.g. River Fleet, River Walbrook). Some detail suggests connection of smaller streams and springs to combined sewers, intercepted to WwTWs.	(Barton 1992, Bolton 2011, Metcalf and Eddy 1914, Myers 2012, Talling 2011).
Tokyo, Japan (Kitazawa Stream)	**Unlikely** – Report details conversion of streams to combined sewers, but now is a storm sewer and not flowing directly to WwTWs. Daylighting separation program is "fake" with stream water pumped from elsewhere and culverted stream remaining buried.	(Hooimeijer and Vrijthoff 2008, Novotny et al. 2010).

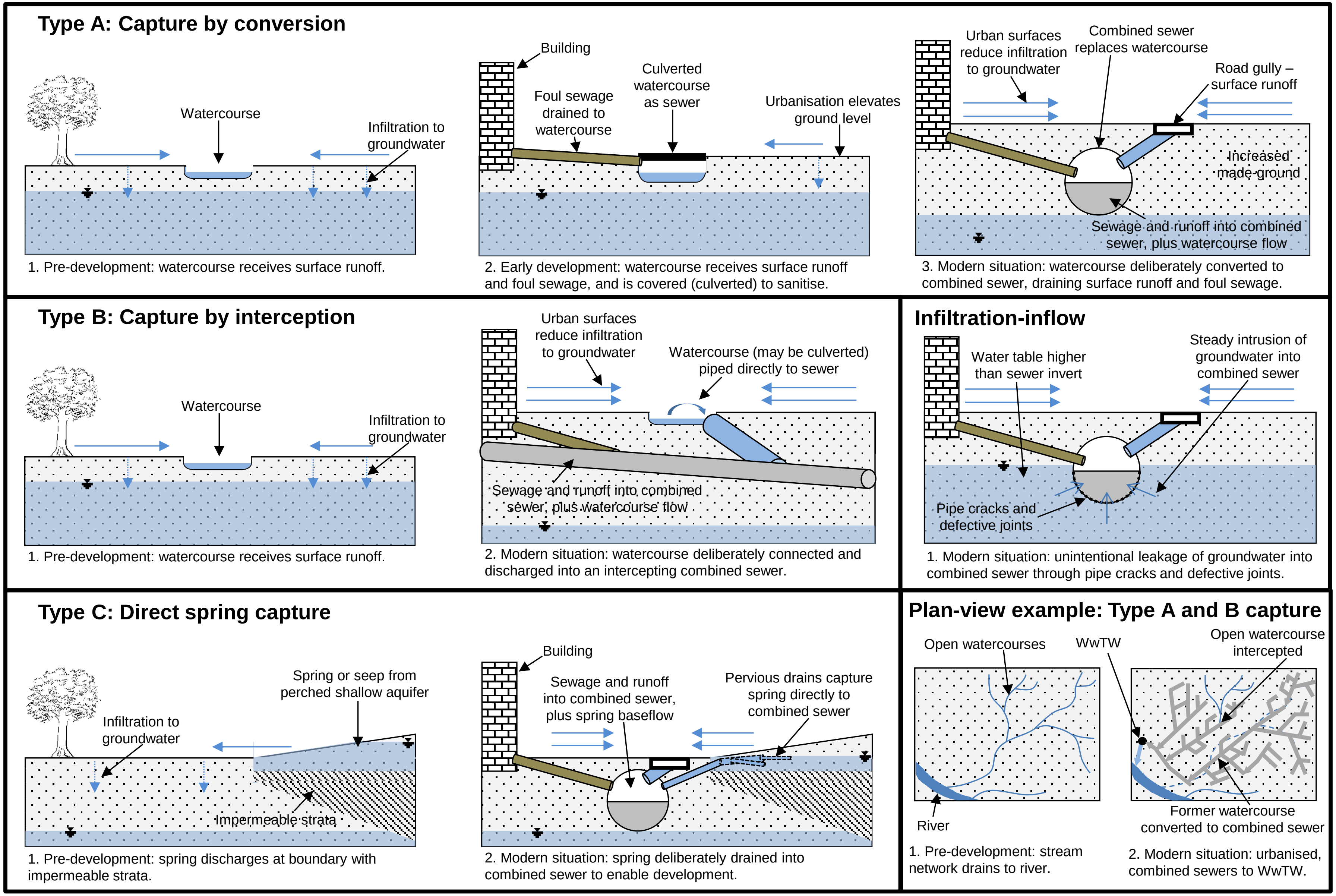
2.3 How and why stream and spring capture occurs

From the reviewed case studies, three modes of entry of captured streams and springs to combined sewers were identified. These are illustrated in **Figure 4Error! Reference source not found.**, and for comparison are shown with infiltration-inflow. First these three types of stream and spring capture are defined, and then the causes are discussed.

2.3.1 Types of stream and spring capture

The first mode of entry (type A) is the conversion of streams and springs to combined sewers. Urban streams were frequently culverted and buried, especially during the period of rapid urban expansion in the 19th century, and some were used directly as combined sewers (e.g. Barton 1992, Conradin and Buchli 2005). The literature is clear that "old sewers were frequently the covered channels of brooks" (Metcalf and Eddy 1914: 5). For example, many of London's smaller spring-fed streams may have been permanently lost from the landscape in this way (Barton 1992, Bolton 2011, Metcalf and Eddy 1914, Talling 2011). In some North American cities, watercourses lend their names to the combined sewers running along their course that replaced them, such as the Garrison Creek Sewer, Toronto, or the Minetta Brook Sewer, New York (City and County of San Francisco 2010, Cook 2011, Duncan 2011a, 2012, Duncan and Barry 2010, Duncan and Head 2010, Griffith 2006, Levine 2008). It can be assumed that, unless it is diverted elsewhere, the clean baseflow of these captured streams and springs is flowing in the combined sewers to WwTWs. The Emscher, Germany and Zenne, Belgium are sometimes considered to be examples of capture by conversion, but are unusual and require clarification. Neither rivers are "lost" or assumed to have been replaced by combined sewers – instead, both are openly adopted as combined sewer canals, receiving local wastewaters. For decades, the Emscher then passed directly through a WwTW before continuing downstream, but wastewaters are now being diverted into a new combined sewer and the river is to be renaturalised (Schulz 2012). The Zenne until 2007 received no treatment at all; new WwTWs and interceptor sewers divert wastewater away from the river, though it continues to suffer from CSO spills (Le et al. 2014).

Figure 4 (Overleaf) Schematic cross-section and plan-view diagrams illustrating typical modes of entry of the three types of capture of streams and springs and infiltration-inflow to combined sewers.


Type A: Capture by conversion
Watercourse
Infiltration to groundwater
1. Pre-development: watercourse receives surface runoff.
Building
Foul sewage drained to watercourse
Culverted watercourse as sewer
Urbanisation elevates ground level
2. Early development: watercourse receives surface runoff and foul sewage, and is covered (culverted) to sanitise.
Urban surfaces reduce infiltration to groundwater
Combined sewer replaces watercourse
Road gully – surface runoff
Increased made ground
Sewage and runoff into combined sewer, plus watercourse flow
3. Modern situation: watercourse deliberately converted to combined sewer, draining surface runoff and foul sewage.
Type B: Capture by interception
Watercourse
Infiltration to groundwater
1. Pre-development: watercourse receives surface runoff.
Urban surfaces reduce infiltration to groundwater
Watercourse (may be culverted) piped directly to sewer
Sewage and runoff into combined sewer, plus watercourse flow
2. Modern situation: watercourse deliberately connected and discharged into an intercepting combined sewer.
Infiltration-inflow
Water table higher than sewer invert
Steady intrusion of groundwater into combined sewer
Pipe cracks and defective joints
1. Modern situation: unintentional leakage of groundwater into combined sewer through pipe cracks and defective joints.
Type C: Direct spring capture
Spring or seep from perched shallow aquifer
Infiltration to groundwater
Impermeable strata
1. Pre-development: spring discharges at boundary with impermeable strata.
Building
Sewage and runoff into combined sewer, plus spring baseflow
Pervious drains capture spring directly to combined sewer
2. Modern situation: spring deliberately drained into combined sewer to enable development.
Plan-view example: Type A and B capture
Open watercourses
WwTW
Open watercourse intercepted
River
Former watercourse converted to combined sewer
1. Pre-development: stream network drains to river.
2. Modern situation: urbanised, combined sewers to WwTW.

The second mode of entry (type B) is capture by interception. Following the Great Stink in London in 1858, where the rivers serving as open sewers frequently failed to fully discharge waste to the River Thames at high tides, Joseph Bazalgette designed a series of interceptor sewers to collect and divert sewage to the Thames Estuary, forming the basis for future combined sewerage development in much of the modern world (Burian et al. 1999, Metcalf and Eddy 1914). The evidence from London and other UK cities indicates that many culverted watercourses, polluted by sewage, were diverted into interceptor sewers and their remaining routes converted into combined sewers (rather than being converted into combined sewers at the source), and now flow to WwTWs (APUR 2001, Barton 1992, Duncan 2011b, IAURIF 2003, Metcalf and Eddy 1914, Myers 2012). In Zurich, some alpine streams are intercepted in the urban area and no longer reach the main river or lake (Antener 2012, Conradin and Buchli 2005, ERZ 2000, 2007, Herrmann 1990). Interception of culverted streams and springs is also explicitly described in many North American cities, where interceptor sewers to WwTWs were installed, often in the 20th century (ALCOSAN 2012, City and County of San Francisco 2010, Griffith 2006, Smith 2007a, Smith 2007b).

The final mode of entry (type C) is the direct capture and drainage of springs and seeps into combined sewers, and, unlike groundwater infiltration-inflow through pipe cracks and joints, is intentional. Historic sewer engineering literature states that early sewer pipes were deliberately leaky (The Manufacturer and Builder 1880) to provide land drainage of springs and seeps or to manage high groundwater levels, such as in Manchester (Read 2004). Other case studies identify spring drainage into combined sewers such as in Zurich (Conradin and Buchli 2005) and London (Metcalf and Eddy 1914), but few provide details of the exact mechanisms. The wider literature acknowledges spring drainage in principle, sometimes as a component of infiltration-inflow (Franz 2007, Metcalf and Eddy Inc. et al. 2004, Uibrig et al. 2002), but this is a direct, intentional connection, specifically not through degraded pipes, that contributes a clean baseflow water to combined sewers.

Not all streams and springs are fully captured by these modes of entry. London’s lost rivers diverted into the high-level, mid-level and low-level interceptor sewers to the WwTW, such as the Walbrook, Fleet, Tyburn and Westbourne, do still discharge to the River Thames during heavy storm events, where the original courses of the rivers serve as CSOs (Myers 2012). Half of London’s watercourses are now culverted (Mayor of London 2009) and while many are apparently “sewerised”, such as the Moselle Brook, they are not all captured into combined sewers, instead providing storm drainage that can nevertheless be polluted. It is therefore likely that many towns and cities have retained partial separation of some watercourses from the combined sewer system, or have disconnected wastewater from culverted watercourses when sewer systems were installed. This is the situation, despite a lack of clarity in the grey literature, in Cincinnati (Metropolitan Sewer District of Greater Cincinnati 2012), Detroit (Bienkowski 2011), some of New York’s lost streams (Duncan 2011a) and Tokyo (Hooimeijer and Vrijthoff 2008, Novotny et al. 2010), where sewerised watercourses do not flow to WwTWs, but remain heavily culverted and often polluted by hidden sewer misconnections, diffuse urban pollution, or spills from CSOs to relieve nearby combined sewers during storm events.

Some reviews, such as in Pittsburgh (ALCOSAN 2012, Pinkham 2001), suggest that less pervious, urbanised catchments have caused springs, seeps and culverted watercourses to be deprived of recharge water and consequently dry up. This may result in a lower volume of captured stream or spring flow reaching WwTWs. However, some studies have demonstrated that urban recharge can still be high (Lerner 1990), so it is likely that buried streams and springs continue to contribute flow to combined sewers. In New York City, localised spring discharges to basements continue in the densely urbanised catchments of culverted and sewerised watercourses, and are pumped and drained into the combined sewers (Duncan and Barry 2010).

2.3.2 Reasons for stream and spring capture

Many natural urban watercourses had become open sewers by the period of rapid urban expansion in the 19th century, as they increasingly struggled to fulfil their historic use of diluting and flushing away discarded waste (Barton 1992, Read 2004). Urban streams that had become open sewers were frequently culverted and buried to provide more sanitary conditions, and this concept is a popular narrative (Cook 2011, Duncan 2012, Duncan and Head 2010, Platform 2012), predominantly explaining the conversion of many smaller watercourses to combined sewers (type A).

The reason for deliberate capture of streams and springs was not just to sanitise watercourses that had become open sewers. Culverting streams, infilling valleys and draining springs and seeps also helped to maximise development space in urban areas, an issue explicitly described in the Pittsburgh case study (ALCOSAN 2012, Pinkham 2000, 2001, Schombert 2006) and in research in cities around the world (Duncan 2011b, Duncan and Head 2010). This engineering practicality is a reason for the conversion and interception of some urban watercourses into the combined sewers. The literature also indicates that culverting streams originally helped to manage surface water flooding, for example in Zurich (Conradin and Buchli 2005) and New York (Duncan 2012). More recently, however, under-capacity culverts in poor structural condition have themselves become a cause of urban flood risk (Wild et al. 2011).

Early sewer design literature also explains the importance of stream baseflow and stormwater to flush the sewage to maintain self-cleansing pipes (Metcalf and Eddy 1914). This could indicate that stream and spring capture was a normal, widespread and even useful practice.

2.4 Identification

In one case study, in Beverley, UK, an historic spring reactivated following a particularly wet season in 2010, and was seen to mix with surface runoff across fields to a combined sewer drain (Ewen 2012). No other published examples have been found where stream or spring capture has been easily visible on the surface; in most cases it is hidden beneath the urban surface and requires other methods to identify it.

No case studies describe a complete methodology to identify captured streams and springs in combined sewers. Drawing on the available information, there are two key requirements. First is the identification of lost watercourses from the urban landscape that may have been culverted into the combined sewers (an indication that streams or springs could be captured). Sometimes this is known from living memory of culvert and sewer development, such as in London (Barton 1992, Metcalf and Eddy 1914), or in Toronto, where photographs show the conversion of the Garrison Creek into a combined sewer (Cook 2011). This is a rare but valuable source of information, though cannot be relied on due to subsequent changes in the sewer system. Further case studies in Detroit, Cincinnati and Tokyo suggest that many claimed captured streams are simply culverted and not directly connected to combined sewers (Bienkowski 2011, Hooimeijer and Vrijthoff 2008, Metropolitan Sewer District of

Greater Cincinnati 2012, Novotny et al. 2010). Connections of lost urban streams and springs to the combined sewer system cannot therefore be assumed, so the second requirement is verification that stream or spring flow is indeed present in the indicated sewers and flows to WwTWs.

Identifying lost watercourses and sewer routes first hand is possible through urban exploration (e.g. Cook 2011, Duncan 2011a, b), but this is only available in accessible, larger sewers. Urban exploration is often undertaken without full safety equipment or permissions from relevant authorities (Myers 2012), and so there are ethical concerns for researchers and the water industry over the use of information derived from it. As streams and springs are often captured at source, secondary information is needed to identify whether they flow to combined sewers. San Francisco has detailed sewer network maps that, combined with historical mapping from 1850, show larger perennial and smaller seasonal watercourses replaced by combined sewers (City and County of San Francisco 2010). In New York, historic sewer network maps show former streams and springs that once covered the city's landscape (Viele 1865). Urban explorers confirm that the Minetta Brook and Tibbett's Brook probably flow to the city's WwTW via interceptors, along with visible direct spring drainage seen from a pipe beneath Spring Street (Duncan 2012, Duncan and Barry 2010), but other culverted streams may be functioning as separate storm sewers and discharge to the Hudson River (Duncan 2011a). Historical maps and clues from street and place names have also been extensively used to locate lost streams, springs and wells in London (Barton 1992, Bolton 2011, Myers 2012, Talling 2011). Relevant information on lost urban watercourses helps to establish the pre-development hydrology, but the usefulness of historic maps depends strongly on spatial and temporal coverage, with many older towns and cities having altered the hydrological landscape before the first available maps. The smallest streams and springs may also not be marked on maps at certain scales, particularly intermittent and ephemeral channels (Meyer and Wallace 2000).

In Pittsburgh, Pinkham (2001) states that the water authority was able to confirm 11 of 20 possible sites where streams flowed directly into combined sewers, but that these were identified by a local engineer (ALCOSAN 2012). They then developed a sequential methodology to identify lost streams using modern maps, records of culverted watercourses and drains (very limited), topographic stream flowpath modelling and historic maps. Topographic modelling to locate historic watercourse routes is an established technique, used for example in New York to map lost catchments from LiDAR data (detailed digital elevation models) of the modern urban surface (Duncan and Barry 2010). In other studies, topographic stream flowpaths have been used to quantify watercourse fragmentation caused by culverts and urban development, differentiating between lost streams with perennial (year-round spring-fed baseflow), intermittent (seasonal spring-fed baseflow) and ephemeral (stormwater runoff only) regimes (Brooks and Colburn 2011, Roy et al. 2009), and predicting their likely water chemistry (Olson and Hawkins 2012). Elmore and Kaushal (2008) used aerial photography to verify modelled topographic flowpaths in the Baltimore area and develop a predictive model of buried headwater streams based on land use classifications. Though this was a separate rather than combined sewer network, they found that up to 70% of headwater streams in small urban catchments were culverted as separate storm sewers.

For the Pittsburgh case study, capture to combined sewers was determined by local engineers from known stream inflow sites and either implied, where mapped sewers followed the course of the former watercourse, or assumed, if no known culverted stream route could be found (Pinkham 2001). In one case, a perennial stream rising from springs in an open park became culverted and within a short distance intercepted by a combined sewer, so stream capture could be confidently identified in the field (ALCOSAN 2012, Pinkham 2001, US Army Corps of Engineers 2009). There is, however, a reliance on local knowledge of lost stream capture to sewers in Pittsburgh; no other case studies had this level of local knowledge. Furthermore, the study did not consider buried springs that may be drained directly into the combined sewer system beneath the urban surface, the location of which reflect hydrogeological rather than purely topographical characteristics.

Neither Pittsburgh nor any other case studies detailed in their methodology the verification of suspected stream and spring flows in the combined sewer, beyond an assumption of connectivity. Equally viable for verifying captured stream and spring flow in combined sewers are the techniques used to detect infiltration-inflow through pipe cracks and joints, reviewed extensively in other papers (UKWIR 2012). Indirect methods include the detection of infiltration (thus potentially stream or spring baseflow) by sewer flow hydrograph analysis, or directly by analysing sewer water chemical signatures to detect a groundwater fed source component in the sewage that would indicate stream or spring-fed baseflow, using indicators such as chemical oxygen demand (COD) or stable isotopes.

Given the minimal published experience in identifying captured streams and springs, this appears to be a key challenge to address by further research. Identification is likely to require multiple lines of evidence, as aside from opportunities arising from local knowledge, no single source of information is likely to identify all modes of entry of captured streams and springs.

2.5 Quantification

Few case studies quantify the volume of clean groundwater fed baseflow in combined sewers and WwTWs from captured streams and springs. Some, such as Cincinnati, Portland and Detroit focus primarily on the stormwater volumes entering combined sewers that could instead be rerouted to the former watercourses (Bienkowski 2011, City and County of San Francisco 2010, Metropolitan Sewer District of Greater Cincinnati 2012), and do not provide an estimate of the captured baseflow contribution reaching WwTWs. Because stream and spring capture to combined sewers will be highly localised within a sewer catchment, of interest is both the proportion of stream or spring flow in specific sewers to identify capacity issues as well as the total contribution of clean water to the WwTW.

In New York, an estimate of the historic Minetta Brook flow in the combined sewer system assumes that the groundwater fed baseflow is the same now as it was in pre-development conditions, based on historic documents (Duncan and Barry 2010). Not only would such historic records be a rare resource, but urbanisation could have altered the urban hydrology, as discussed previously.

In locations where streams are intercepted by combined sewers (type B), it is possible to measure the clean baseflow contribution directly prior to capture. The baseflows of ten perennial streams were surveyed in Pittsburgh, with average measured flows of 8 l/s (range 1-16 l/s) before they entered culverts and were intercepted (ALCOSAN 2012, Pinkham 2001, Troianos et al. 2008). There was no attempt to quantify baseflow of streams and springs converted to sewers at source (type A) or from other direct spring drainage (type C), but it allowed them to identify sewers with reduced pipe capacity and instigate separation programs (Troianos et al. 2008). Similarly in Seattle, 28 l/s baseflow from the Ravenna Creek was measured at the point of intercept to the combined sewer (City and County of San Francisco 2010).

Attempting to scale up the effect of captured streams and springs on the network is more difficult. In Seattle, a local engineer is cited as estimating in addition to wastewater, 4.9 million l/day of wet weather flow (*sic*, assumed to be dry weather flow) and 12.1 million l/day of stormwater flows are present in the network's combined sewers (City and County of San Francisco 2010). It is not clear how this was estimated, and the defined dry weather flow does not differentiate between the contribution from captured streams and springs and that from infiltration-inflow through pipe cracks and joints.

Quantification of captured stream and spring flow in Zurich's combined sewers has been used to analyse the costs and benefits of management options. In 1980, prior to a captured stream separation program, there was an estimated 200-300 l/s of captured stream and spring water baseflow in the combined sewers, plus 400-500 l/s of infiltration-inflow through pipe cracks and joints, and a further 160-220 l/s of other misconnected clean waters (Conradin and Buchli 2005). Despite these figures being republished elsewhere, there is no detail in the original source on how they were derived or calculated, and so they can only be used as an approximate guide. Based on the reported 60-90 million m^3 of wastewater received at Zurich's WwTW in 2010 (Antener 2012), it is possible to estimate that approximately 7-16% of sewage baseflow was from captured streams and springs, and up to approximately 27-54% of the sewage baseflow was steady intrusion of clean water from all extraneous sources including infiltration-inflow.

It is also important to consider the literature quantifying infiltration-inflow to sewers. Studies have variously estimated infiltration through pipe cracks and joints across a whole sewer network to contribute between 15% and 50% of sewer baseflow to WwTWs (UKWIR 2012), and in some studies this figure may include a contribution from the unintentional capture of streams and springs, such as in Prague (Bareš et al. 2012). Identification methods such as hydrograph analysis could also feasibly be used to quantify the volumes attributable to captured stream and spring flow, though might not be able to differentiate this from infiltration-inflow.

The quantity of clean water contributed to combined sewer systems from captured streams and springs will, by its nature, be spatially localised. Of importance to the water industry should be both the total captured flow reaching WwTWs and the potentially high proportions elevating baseflow in individual sewers with critical capacity issues. Quantifying flow from capture by interception may be easier than for other modes of entry, due to it being an identifiable, discrete connection. Generalised quantification figures should be treated with caution, but a WwTW input of 7-16% captured water suggests that this is, along with infiltration-inflow through pipe cracks and joints, worthy of water industry attention.

2.6 Consequences and costs

There are two recognised consequences of captured streams and springs in combined sewers. The first is that clean baseflow reduces sewer pipe capacity and increases the volumes requiring treatment (Butler and Davies 2011, Ellis 2001, Metcalf and Eddy Inc. et al. 2004). This will have a similar impact to infiltration-inflow, for which the many published studies available have been reviewed elsewhere (e.g. UKWIR 2012). The reduction in capacity for stormwater flows and consequent risk of CSO spills and sewer flooding is one of the key drivers for the North American projects on captured streams, following new environmental legislation on watercourse pollution (e.g. ALCOSAN 2012). While captured streams and springs may introduce predominantly clean water and thus have a diluting effect on combined sewage chemistry, they may also introduce sediment and debris (Ellis 2001) as experienced in Pittsburgh (ALCOSAN 2012), or may alter the sewage chemistry where they themselves are contaminated, such as by heavy industrial activities or mine workings.

The second consequence is the loss of urban watercourses from the urban surface, and this shares similar effects to culverted watercourses in general. The wider literature indicates that culverts represent a lost habitat for aquatic and riparian ecology, and a particularly widespread loss of interconnecting blue-green corridors throughout an urban area (Bernet 2010, Roy et al. 2009, Walsh et al. 2005), though there are substantial knowledge gaps here (Wenger et al. 2009, Wild et al. 2011). The water quality of urban rivers can also be impacted by the culverting and disconnection of perennial, intermittent and ephemeral headwaters from stream networks (Kaushal and Belt 2012, Paul and Meyer 2001), as demonstrated especially in Baltimore's separate sewer system (Elmore and Kaushal 2008, Kaushal and Belt 2012, Paul and Meyer 2001). In addition to the environmental impact, they also represent a lost socio-cultural connection to water in the city, with impacts on quality of life, amenity access, aesthetics, land value and urban regeneration, and public health (Wild et al. 2011).

A further impact unexplored in the literature is that the diversion of clean stream and spring flow into sewers represents a major water transfer to the downstream WwTW. This could be depriving upstream watercourses of cool spring-fed baseflow, which could exacerbate the effects of drought on both visual amenity and ecological function.

No studies have been found to explore possible benefits of including captured baseflow, for example to flush sediment or prevent drying of headwater sewers as water efficiency measures are introduced.

No case study has yet provided a comprehensive appraisal of the costs and benefits of stream and spring capture to combined sewers. By drawing on all case studies and the wider literature on infiltration-inflow and urban stream management (Ellis 2001, Franz 2007, Karpf and Krebs 2011, Schulz and Krebs 2004, Walsh et al. 2005, Wild et al. 2011), the impacts of stream and spring capture on water industry costs are summarised as follows:

1. Capital expenditure
    - Land-take costs for larger WwTWs, including larger stormwater storage tanks.
    - Engineering costs of creating the required treatment capacity for increased volumes of more dilute flow.
2. Operational expenditure
    - Chemical and energy costs for increased volumes of water to be treated and pumped.
    - Chemical and energy costs where captured streams and springs introduce contaminated waters.
    - Effluent licensing fees.

- Maintenance costs of sewer networks damaged by excess sewer flows, made increasingly likely due to loss of pipe capacity.
- Maintenance costs of sewer pipes blocked by debris and sediment washed in with stream and spring baseflow.
- Reduced maintenance costs due to baseflow reducing sewer solid build-up.

3. Externalities
    - Environmental, regulatory and public health costs associated with CSO spills, sewer surcharging and sewer flooding, exacerbated by captured baseflow reducing pipe capacity.
    - Ecological and water resources costs of localised droughts exacerbated by diversion of baseflow away from local watercourses to distant WwTWs.
    - Lost environmental, social and economic benefits of open watercourses in the urban environment.

For WwTWs, the approximate effect of captured stream and spring flow on the treatment costs can be estimated based on a proxy of domestic wastewater charging. All UK water companies have a volumetric sewerage charge for metered households. These charges must represent an average marginal cost for wastewater across a range of cities and WwTWs and so provide a cost suitable for national policy analysis. For 2010-11, the cost varied across the UK water companies from £0.53 to £2.67 per m^3 with a weighted average of £1.05 per m^3 (Ofwat 2010c). The water companies do not, in general, have a volumetric charging scheme for stormwater, although three offer a rebate for households which divert all stormwater out of the sewers. Stormwater prices can be used to represent the clean captured water. These rebates average £0.32 per m^3 (range £0.18 to £0.47 per m^3) (Ofwat 2010b).

On this basis, the minimum cost of including a modest stream with a dry weather flow of 1 l/s in a combined sewer system is £33,000 per year if treated as sewage and £10,000 per year if treated as stormwater. As an example, the Esholt WwTW serves Bradford and surrounding areas with a population equivalent of 600,000 in a mostly combined sewer catchment. It recently had a major upgrade costing £53 million (Meneaud 2009). The design dry weather flow is 1350 l/s (wastewater plus clean baseflow from all sources). If the proportion of clean water from captured streams and springs is the same as in Zurich (taken as 16% of dry weather flow), then the annual cost of including this in the sewers is between

£2 million and £7 million. The costs could be significantly higher if infiltration-inflow and stormwater flows were included. For the Ofwat discount rate of 3.5% over 20 years (HM Treasury 2011), this is equivalent to a capital investment (i.e. net present value) of £28 million to £100 million:

$$\mathrm{NPV}(i, N) = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t}$$

Where NPV = net present value, i = discount rate, t = year, R_t = annual expenditure at year t. Note that these figures do not directly represent the costs or benefits of increased baseflow in the sewers, but it can be reasonably assumed that the charging rates must internalise the many direct and indirect consequences of increased baseflows from captured streams and springs.

To provide context for the estimated costs of captured streams and springs, Ellis (2001) has reported that infiltration-inflow to combined sewer systems is costing the UK water industry in the region of £1 million per day.

2.7 Opportunities for management: lessons from a case study of Zurich, Switzerland

The author considers the case study of Zurich to be an exemplar for innovative management of captured streams and springs in combined sewers. The city has been a pioneer of separating captured streams and springs from combined sewers since the 1980s, principally through daylighting watercourses. Since then, various cities across North America have undertaken or proposed stream separation programs (ALCOSAN 2012, City and County of San Francisco 2010, Jencks and Leonardson 2004, Metropolitan Sewer District of Greater Cincinnati 2012, Pinkham 2001, Schombert 2006, Smith 2007a, Smith 2007b). In addition, daylighting of culverted watercourses not captured into combined sewers is also becoming increasingly popular (Broadhead and Lerner 2013, Wild et al. 2011). Zurich was one of the first cities to bring together the issues of stream and spring capture with daylighting.

Since the 1970s, the people of Zurich increasingly recognised the lost social and environmental values of watercourses that had become culverted and had historically been used as combined sewers (Conradin and Buchli 2005, Herrmann 1990). The Bachkonzept (Stream Concept) was a strategic long term plan that arose in the 1980s, aiming to daylight as many culverted watercourses as possible. The literature describes drivers from two different, and apparently equally important, standpoints (ERZ 2000, 2007). First was the public desire to restore culverted watercourses to revive lost living space and quality of life, and second, the water authority's recognition of clean water flowing to WwTWs requiring unnecessary sewer capacity, reducing wastewater treatment efficiency and increasing costs. Consideration of WwTW costs is unique to Zurich; no other case studies consider this in detail, though it is briefly discussed in the Pittsburgh case study (Pinkham 2001). The stated aims of the Stream Concept are (Conradin and Buchli 2005): separate and direct flow of unpolluted extraneous water to receiving waters, creation of recreational space for different communities, enhancement of living areas, and creation of living space for animals and plants.

Importantly, this concept was adopted by the City Council in 1988 as a planning policy, and incorporated into the 1991 Water Pollution Law (at the county level). The Swiss Water Protection Act later encouraged a process of combined sewer separation using daylighted streams as the primary surface water drainage system (Swiss Confederation 1991):

> "Article 7. Non-polluted wastewater shall be infiltrated according to the instructions of the [county] authorities.
>
> Article 12. Non-polluted wastewater with permanent flow shall not be passed through a central [WwTW]."

There is no published technical detail on how the lost streams and springs were identified. Maps illustrate the historic burial of watercourses entering the urban area (**Figure 5**). While the literature does not detail the connectivity of the captured streams and springs to the combined sewer system, using the concepts in **Figure 4**, it is hypothesised that many are capture by interception (type B) of alpine streams flowing into the city into combined sewers. There may also be additional capture by conversion (type A) to combined sewers of streams rising within the urban area. The literature explicitly acknowledges direct spring capture (type C) (Conradin and Buchli 2005).

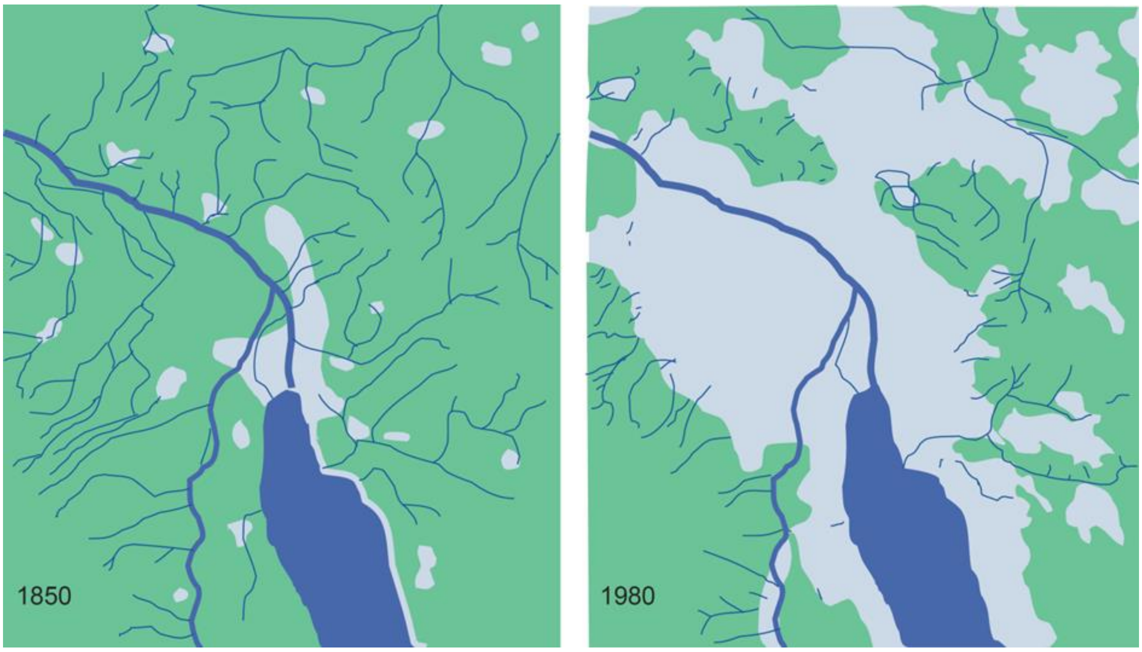


Figure 5 Historic loss of Zurich's streams (water in blue) with increasing urbanisation (grey). Many streams now flow in culverts, or are diverted into combined sewers. Since 1980, 20 km of streams have been daylighted, with plans for many more (ERZ 2000, 2007). (Image courtesy of Markus Antener, ERZ).

A conventional approach to converting combined sewers to separate foul and stormwater systems would be to install drainage pipes – as recommended in the USA (United States Environmental Protection Agency 1999) and exemplified in a German report (Unknown 2009). The Stream Concept's innovation lies in the creation or restoration of lost urban streams to convey captured stream and spring baseflow, as well as a proportion of stormwater runoff from existing and new developments (**Figure 6**). They therefore act as a form of sustainable drainage system (SuDS) (Conradin and Buchli 2005), and play a role in urban flood risk management (Antener 2012). Naturalistic stream channels and riparian corridors are used where possible, but where space is limited, engineered "street streams" are installed. The latter may have a lower ecological potential, but nevertheless offer architectural value in urban areas (**Figure 7**). In one known case, a "street stream" along Nebelbach, Zurich, overflows into the combined sewer to prevent flooding during heavy rainfall periods. There has not, to the author's knowledge, been an independent published assessment of the hydrological performance (particularly with regards to localised captured baseflow and stormwater separation and effective reductions in combined sewer flows), or the ecological and social benefits from the daylighting of captured watercourses, though the literature makes general claims of improved land values, quality of life and wildlife in urban areas as key results (Antener 2012, Conradin and Buchli 2005, ERZ 2000, 2007).

Based on the reported 60 million m^3 of wastewater flowing annually to Zurich's WwTW (Antener 2012), captured stream and spring flow originally contributed approximately 16% of the influent, and this has been reduced to around 10% using the Stream Concept (**Table 3**). This moderate reduction has been used for gauging the cost-benefit of captured stream and spring separation using daylighting, in addition to the social and environmental benefits. Conradin and Buchli (2005) state savings of CHF 5000 per l/s (approximately £3300) of clean stream or spring water diverted away from the WwTW, based on undisclosed unit treatment costs. This is significantly less than the estimated £33,000 annual costs of including a stream of 1 l/s in the combined sewer, based on water charging rates. The evidence indicates that savings are nevertheless possible, and precise economic evaluation is required. They also state that daylighted streams are cheaper than installing separate drainage pipes in urban areas (CHF 1000-2000 and CHF 2000-3000 per metre length, respectively) (Conradin and Buchli 2005). Additionally, some costs have been reduced by integrating daylighting projects with unemployed labour forces.

Table 3 Estimated flows of clean water sources in Zurich's combined sewer network (Antener 2012, Conradin and Buchli 2005), showing the effect of the Stream Concept on separating captured streams and springs from the combined sewers by daylighting urban streams.

	Prior to Stream Concept (1980)	**Separation possible with Stream Concept**	**Separation so far with Stream Concept (2010)**
Spring and stream water	200-300 l/s	180-250 l/s	140-190 l/s
Other misconnected clean waters	160-220 l/s	50-80 l/s	30-40 l/s
Infiltration-inflow	400-500 l/s	50-100 l/s	50-80 l/s
Total	760-1020 l/s	280-430 l/s	220-310 l/s

Figure 6 (Overleaf) Schematics showing alpine streams and springs intercepted and captured into Zurich's combined sewer system, circa 1980 (1); conventional sewer separation of captured streams and springs and stormflow into separate pipes (2); and the Stream Concept approach of separating captured streams and springs into daylighted urban watercourses (3). After Novotny et al. (2010) and Conradin and Buchli (2005).

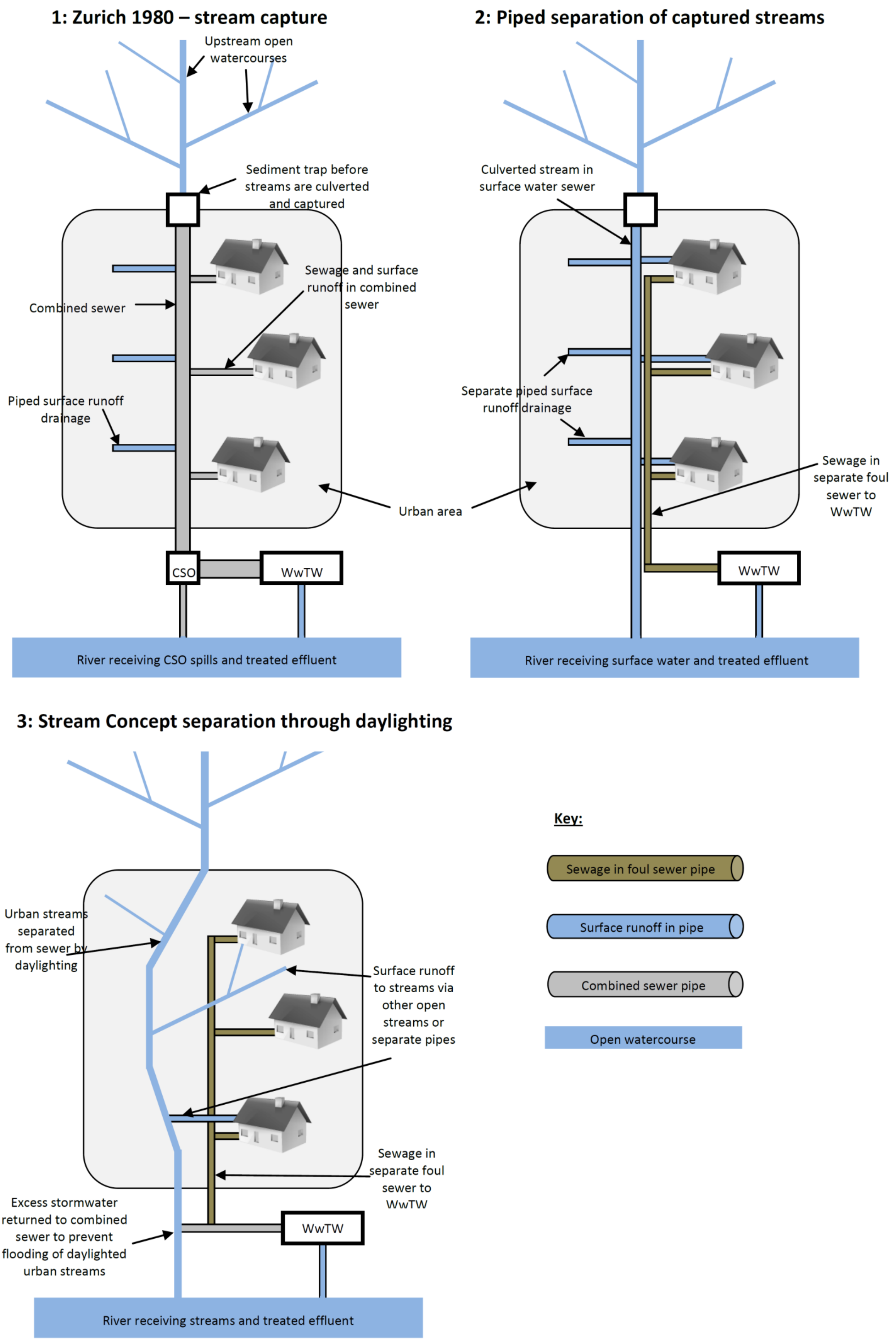

1: Zurich 1980 – stream capture
Upstream open watercourses
Sediment trap before streams are culverted and captured
Sewage and surface runoff in combined sewer
Combined sewer
Piped surface runoff drainage
Urban area
CSO
WwTW
River receiving CSO spills and treated effluent
2: Piped separation of captured streams
Culverted stream in surface water sewer
Separate piped surface runoff drainage
Sewage in separate foul sewer to WwTW
WwTW
River receiving surface water and treated effluent
3: Stream Concept separation through daylighting
Urban streams separated from sewer by daylighting
Surface runoff to streams via other open streams or separate pipes
Sewage in separate foul sewer to WwTW
Excess stormwater returned to combined sewer to prevent flooding of daylighted urban streams
WwTW
River receiving streams and treated effluent
Key:
Sewage in foul sewer pipe
Surface runoff in pipe
Combined sewer pipe
Open watercourse

Figure 7 Daylighting urban streams for captured stream and spring separation from combined sewers: the experiences of the Zurich Stream Concept. Left: daylighted Albisrieder Dorfbach with naturalistic bed in a spacious suburban location, with ecological and social benefits (image courtesy of Markus Antener, ERZ (2000)). Right: daylighted Nebelbach in dense Zurich centre, illustrating innovative methods of creating engineered street streams with urban regeneration benefits (author's own photograph).

The financial justification for daylighting based on wastewater treatment costs of captured streams and springs is unique to Zurich, but additional ecosystem services and socio-cultural benefits (including land value improvements) derived from the uncovered, separated streams are discussed in other case studies (e.g. City and County of San Francisco 2010, Pinkham 2000, 2001) as well as more generally in literature on daylighting (e.g. Broadhead and Lerner 2013, Wild et al. 2011) and in studies on sustainable urban river corridor management (e.g. Pattacini et al. 2011). This indicates that Zurich's authorities are confident in their understanding of the concept of captured streams and springs, its consequences and costs, and the viability of separation. Despite this position, no peer-reviewed literature has independently verified these claims of economic benefits for wider scrutiny. In particular, it is not clear how these flows and costs have been estimated, restricting use of the figures as an indicative guide.

Zurich's Stream Concept, with legal and policy backing, effectively requires integrated management of wastewater, surface water drainage, watercourse restoration and urban design. Many of these concepts are now called for in Green Infrastructure or Water Sensitive Urban Design. While not a panacea, daylighting streams to separate clean flows from combined sewers could help with existing efforts to tackle problems of urban water quality (such as revealing misconnections and diffuse urban pollution) and quantity (such as surface and river flooding). It could, subject to an assessment of hydrological performance, be applied in strategic areas to address critical sewer capacity and flooding issues.

Policy and governance issues will almost certainly require further exploration. The smallest headwater streams, those most vulnerable to culverting and capture into either combined or separate sewers (Bishop et al. 2008, Elmore and Kaushal 2008), are offered only limited protection such as in the USA Clean Water Act (Elmore and Kaushal 2008) and in Europe can be neglected in the Water Framework Directive (Lassaletta et al. 2010). It will also be important to consider the responsibilities and management implications of historic captured streams and springs reclassified from natural waters to sewer assets. In the UK context, this may necessitate further integration of water management that is currently shared between privatised water companies, local authorities, private developers and the Environment Agency; the water industry should now consider the approach in Zurich as a means of bridging multiple goals in sustainable water management.

2.8 Conclusions

There is case study evidence that streams and springs have historically been captured into combined sewer systems, often to maximise development space and sanitise polluted watercourses. They contribute clean water baseflow to WwTWs, and the experience from Zurich indicates the quantity could be substantial, with 7-16% of baseflow reaching WwTWs from clean, captured water. However, this capture has been little discussed or acknowledged until now, with most published research on steady intrusion of extraneous flows to combined sewers focusing on the related problem of infiltration-inflow through pipe cracks and joints. The evidence suggests that captured streams and springs have a similar impact to this: higher risks of sewer flooding and CSO spills and increased treatment costs.

This review suggests that it is highly probable that clean baseflow from captured streams and springs is reaching WwTWs in some towns and cities in the UK, and concludes that there is a strong case for identifying and quantifying captured streams and springs in UK sewer networks, particularly with water industry interests in reducing CSO spills and sewer flooding, future-proofing pipe networks by conserving capacity, and reducing operational costs of wastewater treatment (e.g. Kelda Group 2011).

Indicative costs of treating this clean baseflow suggest economic benefits of separating it from combined sewers. The Zurich Stream Concept presents an enticing opportunity to combine water industry and river restoration interests. By using daylighted urban streams to convey the clean water baseflow, highly promising social and environmental benefits have been suggested; an independent peer-reviewed appraisal of this approach would be strongly recommended.

3 Indicating stream and spring capture in combined sewer systems: a multiple lines of evidence approach for network-wide assessment

3.1 Introduction

Streams and springs can become "lost" by having been not just culverted below ground but directly connected into combined sewer systems. As a source of clean water to combined sewer networks in addition to infiltration-inflow through pipe cracks and defective joints, there is a case for water companies to identify where stream and spring capture occurs, quantify it and evaluate the consequences for WwTW and sewer network operations (Chapter 2). Loss of headwater streams in this way also brings environmental and social disbenefits (Everard and Moggridge 2012, Freeman et al. 2007, Meyer and Wallace 2000, Nadeau and Rains 2007, Walsh et al. 2005).

While some watercourses may be directly intercepted by a combined sewer so that a discrete inflow can be observed or checked with connectivity tests, some watercourses have been converted into combined sewers from their source and have no known or easily identifiable point of entry to a sewer. In-sewer methods may be able to indicate the presence of captured waters in a sewer, as with infiltration-inflow. Because they may first require suitable inspection locations to be identified, they may be inappropriate for a pro-active network-wide assessment. While some studies have attempted to map and quantify rates of stream burial (Bishop et al. 2008, Brooks and Colburn 2011, Elmore et al. 2013, Elmore and Kaushal 2008, Galster 2012, Roy et al. 2009, Stammler et al. 2013), there are few international and no UK examples of a strategic attempt to identify and tackle stream and spring capture. As such, there is no methodology available to the water industry.

The research aim of this study is to develop a methodology that can be used to indicate where stream and spring capture occurs in combined sewers, by critically reviewing and applying available evidence to a UK case study. Three stages are considered: first, *locating* lost streams and springs; second, *indicating* where they may be captured into combined sewers; third, *verification* options available to confirm or rule out suspected capture. Key questions to be answered are:

- What evidence is available to locate lost streams and springs and indicate capture, and what are the uncertainties of this?
- How many streams and springs may have been "lost" in the case study catchment?
- How many streams and springs may have been captured in the case study catchment?
- What further work is required?

3.2 Review of evidence

3.2.1 Locating lost streams and springs

Modern maps

Modern maps establish the current known hydrological network of springs and open and culverted watercourses. Surface water features can be identified from a range of products in the UK, such as Ordnance Survey (OS) Mastermap (vector) and OS Landplan 1:10,000 (raster) products. The Detailed River Network product by the Environment Agency is a modified version of the OS Mastermap watercourse network covering England and Wales, with the routes of culverted sections included from local surveys and available information (Coley et al. 2012). Errors in culvert routes are possible where information about their exact route is not available, and can be indicated by apparent straight lines joining culvert openings. This product is annually updated and revised. The Mastermap and DRN products are in vector format with searchable attribute tables in which "springs", "seeps", "issues", "sinks" and "collects" and "culverts" can be located.

In the UK, OS maps do not generally differentiate the permanence of watercourses or springs, and it is not clear the extent to which headwater delineation considers the hydrology or geomorphology, or whether this is the cartographer's subjective and aesthetic choice (Boitsidis et al. 2006). This is in contrast with the USGS Topographic Maps that cover most of the United States and differentiate watercourses with solid lines (perennial watercourse) and dashed lines (intermittent watercourse, flow associated with seasonal groundwater fluctuations) (Meinzer 1923). However, numerous studies have demonstrated that the USGS marked channel initiation points of perennial, intermittent and ephemeral watercourses are not always reliable and the differentiation between flow permanence is not based on hydrological data – seasonal and permanent hydrological changes to catchments or burial of headwaters are some factors that make the marked channel initiation points inaccurate (Brooks and Colburn 2011, Meyer and Wallace 2000).

Historical maps

Historical maps can be used to identify the stream network and location of springs prior to culverting or other urban development. Digitised, georeferenced maps are available for most of Great Britain at a range of scales from the 1840s onwards. These include the OS County Series at 1:2,500 and 1:10,560 scales, first published between 1846 and 1893 (depending on the county), with subsequent revision and resurveying three times before the first National Grid maps from 1945 at 1:1,250, 1:2,500 and 1:10,560 scales, with multiple revisions until the present day. In larger towns and cities, the highly detailed OS Town Plans were produced at 1:500 and 1:1056 since the 1850s. All these show streams and springs, but the available detail depends on several factors.

First is the scale and style of the map type. Smaller watercourses are generally marked as a single line and not always labelled, which can make them indistinguishable from other boundary or field lines like hedgerows. Historically, many parish or field boundaries followed natural watercourses and even today subtle meandering can be seen occasionally in subsequent housing development along those original boundaries. Watercourses are labelled on some maps with an arrow marking flow direction, but not in all scales and ages (**Figure 8**). Not all water features are shown on all map scales, and this may relate to the original survey scale or the modifications used to *derive* the map from surveys at other scales. For example, the 1:2,500 County Series maps omit details such as springs found on the smaller scale 1:10,560 County Series maps (Oliver 2005), though in most cases it contains more detail. Likewise, terminology is not always consistent across the map scales and ages, and there are several guides to aid interpretation (Harley 1964, 1975, Lockey 1980, Oliver 2005). Terms of interest are (Oliver 2005):

- CS; CCS; COCS; CD; CR – label denoted to dashed lines that can refer to the centre of a stream, centre of a covered stream, centre of old course of a stream, centre of a drain, or centre of river or road.
- Spring; Spr – where the source is a natural spring.

- Issues; iss – where the source is an emission from an agricultural drain, or where the stream re-emerges from underground.
- Collects – where the source is a bog or marsh.
- Sinks – the point where a stream disappears underground.

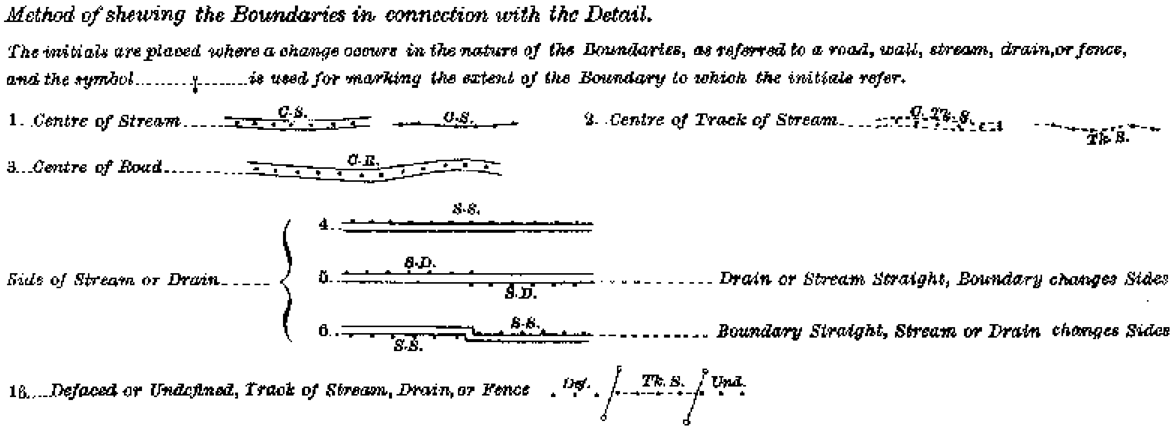


Figure 8 Detail from legend of OS 1:2500 County Series maps between 1843 and 1893, illustrating some of the ways in which streams are shown (source: British History, http://www.british-history.ac.uk/report.aspx?compid=40955).

The second factor is the age of the map. Many watercourses in both urban and agricultural areas had already been culverted or modified to some extent by the mid-19th century. The earliest OS maps are therefore not old enough to cover pre-development locations of watercourses and springs. Furthermore, the spatial coverage of the earliest maps is often limited to the extent of the built area at the time of the survey.

The OS County Series and Town Plans remain some of the first widely available and consistently surveyed maps, but there may also be local historical tithe, parish and town maps available. Maps dating back to the middle ages are sometimes available, though this brings challenges in interpreting and accessing them. They are not always available in a digital format, and may require scanning, rubber-sheeting and georeferencing to import them into a useable GIS format. Alternatively they can be visually interpreted, but this may reduce the accuracy with which locations of springs can be determined.

No known historical maps have been digitised in a searchable vector format, making searching through the maps at various ages and scales relatively time-consuming. In the US, historical topographic maps exist and are freely available from the late 19th century and have been used in some studies to map stream burial patterns (Galster 2012).

Street names and place names

Street and place names can often reflect the presence of water nearby. They are also easily searchable from attribute tables in OS GIS products such as Vectormap Local, Gazetteer and Mastermap. Historical gazetteers can also be found for some localities, providing details of streets that may since have been removed or renamed. As a historical interest, local history books may be available to guide on the etymology of the names. Names that may reflect watercourses and springs include “spring” (e.g. Spring Terrace), “river” (e.g. Riverdale Close), “brook” (e.g. Brook Street) and “bourne” (e.g. Wybourn).

Citizen science

The contribution of “citizen science” for local knowledge and history should not be underestimated, though it can be difficult to robustly verify claims. The public can provide relevant information such as springs flowing in back gardens or flooding basements, old watercourse culverts under their property, or even first-hand memories of now culverted watercourses. Data can be manually mapped in GIS to the closest determinable location.

Other information

Numerous useful secondary sources are available to locate former streams and springs. Modern texts as well as first-hand historical texts on local history may include references to watercourses or springs, especially where these may have formed local boundaries or provided notable sources of drinking water in previous centuries. Paintings can also show historical water features. Local planning departments or local libraries may also have records of engineering designs for watercourse culverting and modifications. Such qualitative data can be manually mapped in GIS to the closest determinable location, which may be difficult and require interpretation with old maps. Typical descriptive findings from historical texts are:

> “An open stream ran from the top of Cornish Street, in front of Green Lane, and emptied itself in the Don, below where Green Lane works now stand,” (Leader 1875: 144).

> “…while Watery street was a rural lane with a stream running down it,” (Leader 1875: 145)

> "We know, further, that the great entrance to Broom Hall was at the foot of Clarence Street of to-day, with the horse-dyke stream tumbling down the slope of Leavy Greave close to those gates," (Stainton 1924).

It is difficult to verify this information. Just as paintings can be impressionistic, so too can written reminiscences or histories of places: the author may have written in an authoritative tone, but could have incorrectly remembered the area or perpetuated a local myth. This is demonstrated by the many authors trying to locate the lost rivers of London: Barton (1992) describes how several widely reported or claimed lost rivers do not appear to have ever been real watercourses.

Topographic flowpath modelling

Delineating stream networks from topographic data is a widely used GIS technique, using extensions such as HydroTools in ArcGIS software. Studies have used this to assess the extent of stream burial in North America (Elmore and Kaushal 2008, Roy et al. 2009, Stammler et al. 2013). The basic operation begins with a topographic digital terrain model (DTM) map for the catchment area, which is a grid of "cells" each specified with an elevation. It calculates the slope for each cell in the dataset and corrects the data to remove any topographic "sinks" (i.e. it smoothens local depressions so that each cell has a neighbouring cell of lower elevation, and therefore a continuous flowpath can be derived). It then calculates a flow direction and contributing flow accumulation value for each cell (i.e. the number of upstream cells of a given point). A threshold value is chosen that represents the contributing upstream area required for channel initiation, downstream of which a stream is delineated.

This method is therefore based solely on topography, with no consideration of the physical or hydrological processes that influence stream networks. At a catchment scale, it provides a means to demarcate valley shapes and the approximate location of the valley bottoms. Two important factors determine the output:

Topographic input data. There are no historical DTMs widely available for the UK, though it may be possible (and time consuming) to digitise the contour lines from historical maps. Modern DTMs reflect the current ground surface without the subsequent changes and made-ground associated with urban development over the centuries. This introduces uncertainty over the use of such data to predict the flowpaths of former streams buried beneath urban development, but it is expected that even largely infilled valleys may still be possible to identify in some cases. For the UK, good quality topographic data at a range of scales exist. The OS Landform PROFILE DTM product is interpolated from contours surveyed at 1:10,000 at a 5 m vertical interval with reported vertical accuracy greater than ± 2.5 m, presented as a 10 m horizontal grid, and is of comparable resolution to the data used by North American studies (Elmore and Kaushal 2008, Roy et al. 2009, Stammler et al. 2013). More detailed topographic data derived from LiDAR (Light Detection And Ranging) methods are increasing in availability for the UK, with most urban areas now covered at up to 25 cm horizontal spatial resolution and 5 cm vertical accuracy. LiDAR is proving useful in fields where such precision is advantageous, such as modelling topographic flowpaths of surface water through urban areas where street curbs and small topographic variations are important (e.g. Maksimović et al. 2009) and some studies recommend LiDAR for stream delineation (Colson et al. 2006, Metz et al. 2011). LiDAR data comes at increased costs and data storage requirements, and such detail may be redundant where the focus is finding catchment scale watercourse valleys.

Stream initiation. The flow accumulation threshold, because it does not consider physical and hydrological processes, is a crude proxy for channel initiation (Montgomery and Dietrich 1988, 1992, Montgomery and Foufoula-Georgiou 1993, Tarboton et al. 1991). It could be used as a parameter to calibrate the modelled flowpaths against observed channel initiation points in a relatively undeveloped area with similar soil and geology types. Studies have shown that this can underestimate actual stream length, especially because so many urban and rural streams have been modified and have had their headwaters piped (Bishop et al. 2008, Brooks and Colburn 2011, Elmore et al. 2013, Elmore and Kaushal 2008, Galster 2012, Julian et al. 2012, Pennino et al. 2014, Roy et al. 2009, Stammler et al. 2013). It is therefore recommended that the threshold be set to overestimate stream length, and that the output be interpreted as an approximation.

Hydrogeology

The location of springs is determined by the geology and groundwater level. The UK has full coverage of surface bedrock and superficial deposit geology data from the British Geological

Society (BGS), from which information about the likely permeability can be derived. In many areas, groundwater outcrops can be associated with geological springlines, where a permeable rock layer overlays a less permeable rock layer. Soil types may also be important local controls on groundwater, and there are widespread soil data for the UK that provide typical permeability or reflect typical groundwater depths. Nevertheless, detailed groundwater models are not generally available in the UK.

Direct groundwater observations can be provided by borehole monitoring sites used for assessing national water resources, but there are too few to enable confident predictions of local depths to groundwater, especially in areas of complex geology and where multiple shallow aquifers are the dominant source of spring flow. Historical borehole records are widely available from the BGS with dense coverage in most areas (because they are associated with drinking water boreholes as well as trial boreholes for construction sites). These can provide useful observations about the depth to groundwater – there may be multiple aquifers in a system, some with artesian pressure – but care must be taken in the interpretation in instances where groundwater observations were not a primary concern or where boreholes were dug in dry years. Drinking water abstraction may be an important current control on groundwater levels and thus influence the flow of springs. Past coal mining also may have considerably lowered water tables through purposeful pumping, causing springs to dry up, and the UK Coal Authority may be able to advise from records where they expect groundwater levels to be lowered or recovering. There may also be numerous local studies that detail the hydrogeology.

3.2.2 Indicating stream and spring capture

Having predicted the location of lost streams and springs, additional evidence must be evaluated to indicate where these may now have been captured into the combined sewer system. The method and uncertainty associated with these lines of evidence is now discussed.

Sewer network maps

Sewer network maps are essential to indicate the different types of stream and spring capture. Capture by interception, a direct inflow of a culverted or open watercourse to a combined sewer, can be indicated where a mapped watercourse (e.g. from OS Mastermap or DRN data) connects directly with a combined sewer in the sewer network data. Uncertainty may arise due to data quality issues (such as uncertainty over the true positions of culverts), and therefore additional evidence to confirm connectivity may be important.

Many combined sewer networks do not exclusively contain combined sewers; separate surface water pipes may exist locally and may drain water (stormwater, a culverted watercourse, a captured stream or spring, or a mixture of these) to a downstream river or even to a downstream combined sewer. Such direct connections to combined sewers should also be evaluated to consider whether they coincide with the predicted locations of a lost stream or spring.

Where there is no known discrete inflow of a stream or spring to a combined sewer (i.e. capture by conversion or direct spring capture), comparing the predicted locations of lost streams and springs to the sewer network map can identify whether the route of a lost stream appears to have been replaced by a combined sewer or whether there are plausible surface water pipes or culverts conveying the clean water to a downstream river. If no alternative flow routes are identified, it should be assumed that capture is possible, and further evidence sought.

In all cases, uncertainty may arise where it is not possible to observe the actual water source, because it may no longer flow due to changes to catchment hydrology. Uncertainty may also arise due to data quality – while there are statutory sewer network maps available across the UK, details about the precise locations and sewer characteristics can be uncertain.

Depending on the detail available in the GIS attribute database for the sewer network, some surface water sewers may be denoted with the legal status of "old watercourse" or similar. It would be expected that these exist in locations where lost streams and springs had been predicted.

Night-time minimum flow methods

Dry weather sewer flow follows a diurnal pattern: elevated during the daytime with distinct peaks in the morning and evening, and lower during the night-time reaching a minimum at around 4 a.m. The exact pattern depends on the characteristics of the contributing sewer catchment and the people and businesses in it. Studies estimating the contribution of infiltration-inflow to combined sewer systems often equate the dry weather sewer flow at the night-time minimum to infiltrating waters (Butler and Davies 2011, Metcalf and Eddy Inc. et al. 2004). Various hydrograph separation techniques have been proposed to improve the estimate of the actual infiltration-inflow proportion, looking at recession curves (Weiß et al. 2002, Wittenberg 1999) or pairing the method with chemistry markers (Bareš et al. 2009, 2012, De Bénédittis and Bertrand-Krajewski 2005a, b, Houhou et al. 2010). Night-time minimum flow techniques generally assume that infiltration-inflow is a constant baseflow, though studies have demonstrated that it varies seasonally with fluctuations in groundwater depth (e.g. Wittenberg and Aksoy 2010).

While the focus of such studies has been on infiltration-inflow through pipe cracks and defective joints, there is no reason why such methods could not be applied to indicate elevated baseflow associated with captured streams and springs.

Observed flow data are not available for every sewer in every network, but water companies do collect flow data in order to develop sewer hydraulic models. Where flow data are available directly, the accuracy of evaluating the baseflow proportion will be limited without consideration of the upstream contributing area that may result in an observed lag time in the hydraulic response of the sewer catchment. In this respect, a well-calibrated sewer model derived from sufficient flow monitoring data may even improve the confidence.

If such models already exist, they could provide a relatively straightforward and quick indication of elevated night-time minimum flow across an entire sewer network using existing data. It would be expected that combined sewers in the vicinity of lost streams or springs display elevated night-time minimum flow. It would be difficult to differentiate stream and spring capture from infiltration-inflow, because this is an indirect observation rather than direct observation of connectivity. If models do not exist, it may be feasible to collect flow data for further investigation of suspected capture.

Sewer water balance

It is theoretically possible to use a water balance approach to identify elevated extraneous water flows in a sewer. During dry weather (thus ignoring the influence of rainfall runoff) the catchment sewer outflow should correspond to catchment inflows (measureable by a metered water supply); minus water losses attributed to leakage, evapotranspiration, "export" of consumed water or direct groundwater recharge; plus gains in water from groundwater infiltration-inflow, mains water pipe leakage, or captured streams and springs.

Many water companies monitor water supply flows typically at a neighbourhood scale and this could be paired with sewer flow monitoring data. This would be most effective where the water supply and sewer network metering areas are the same (but they are not always the same) and it is likely that this method would make use of existing data. There will also be considerable uncertainty in measuring or estimating water losses, but these would cause an underestimation of infiltration-inflow or captured water. If the water leaving a metered area in a sewer exceeds the inputs of water to that area in a combined sewer where stream or spring capture is suspected, this could provide additional evidence of capture. It would again be difficult to differentiate capture from infiltration-inflow.

Water chemistry methods

Various chemistry based methods may be appropriate to indicate the presence of stream and spring capture in a combined sewer. Studies detecting infiltration-inflow have used unique markers or have combined markers with sewer flow hydrograph methods. Such methods may be appropriate for detecting captured streams and springs, as the water is similar or the same. However, water typing – which differentiates water sources on the relative balance of chemical constituents rather than the presence or absence of a specific marker – may be more appropriate. Chapter 4 presents the development and successful application of major ion water typing that has been able to satisfactorily indicate stream and spring water mixing in combined sewers.

Appropriate data are unlikely to already be available, so these methods would require specially commissioned sampling and analysis.

3.2.3 Verifying stream and spring capture

For direct inflows of capture by interception, capture can be verified by connectivity or dye testing to confirm the flow of an open or culverted watercourse or surface water sewer "old watercourse" into a combined sewer.

For capture by conversion or direct spring capture, verifying capture may require highly specific site investigation, such as spiking groundwater with a dye or marker, which may be inappropriate or unfeasible. The previous methods to indicate capture therefore provide the best available evidence. It may be possible to use the available evidence or tests to rule out capture rather than positively identify it in a combined sewer.

Where capture cannot be easily or confidently verified, a multiple lines of evidence approach is required. This considers the reduction in uncertainty for each additional line of evidence against the increased data collection or analysis costs for additional evidence. Where lines of evidence disagree, then the relative confidence or uncertainty associated with each would need to be assessed. Evaluating the confidence and costs of the lines of evidence may be appropriate to combine them into a decision making tool suitable for indicating stream and spring capture. Chapter 5 develops a Bayesian Belief Network that uses expert knowledge to assess the relative weight of some of the methods to locate lost streams and springs.

3.3 Case study application

3.3.1 Site description

Sheffield is a typical city in northern England. It has a hilly topography, and lies at the confluences of the rivers Sheaf, Loxley, Rivelin, Porter and Don. The city expanded particularly during the industrial revolution and into the 20th century, and subsequently many watercourses were modified or culverted. Sheffield is served by a predominantly combined sewer network, but separate sewers are found in some developments and suburbs and there are several surface water pipes found within otherwise combined sewer areas. The network drains approximately 285,000 m^3/d of wastewater to Blackburn Meadows WwTW near Rotherham (Green 2002). The old combined sewer system has chronic and acute capacity problems, and there is considerable operational expenditure at the WwTW for pumping and treatment energy (Bob Anderson, Yorkshire Water, pers. comm. November 2012). The water company, Yorkshire Water, has expressed an interest in relieving sewer flooding and generating extra capacity using SuDS approaches (James Kitson, Yorkshire Water, pers. comm. January 2011). Sheffield City Council is exploring opportunities to reopen (daylight) buried watercourses for multiple environmental and urban regeneration benefits (Creative Sheffield 2008, Sheffield City Council 2010). A search area of 89 km^2 was delineated that includes the city centre and some of the older suburbs, including the majority of the River Sheaf and Porter Brook catchments.

3.3.2 Method and information sources

All information sources for locating lost streams and springs were compiled for Sheffield: modern maps, historical maps, street and place names, citizen science, other information, topographic flowpath modelling and hydrogeological information (**Table 4**).

For the topographic flowpath modelling, the flow accumulation threshold for modelled topographic flowpath channel initiation points was calibrated against 61 training points of observed stream initiation from the historical maps and modern maps. As previously discussed, studies have highlighted that many urban headwater streams have been piped and so the topographic flowpaths may underestimate stream length; it is more favourable to overestimate stream length at this stage to avoid prematurely ruling out potential lost streams. Seven flow accumulation thresholds were tested, measuring the distance between the training point and modelled topographic flowpath stream origins, with a positive distance reflecting underestimation and negative distance reflecting overestimation (**Figure 9**). A flow accumulation threshold of 4 ha (400 cells on a 10 m resolution DTM) was chosen, erring on the side of overestimation (mean -110 m; σ=260; n=61). The large standard deviation reflects considerable uncertainty in both the technique and its underlying assumptions and in the ability to precisely locate training points of known stream origins from maps, further supporting the need to be conservative. To test how closely the topographic flowpaths could predict lost streams and springs, the locations were then compared to the known stream locations derived from modern maps and historical maps.

Lines of evidence to indicate stream and spring capture are detailed in **Table 5**.

Table 4 Locating lost streams and springs: case study data sources and details for the lines of evidence.

Type	Data source and details
Modern maps	Edina Digimap / Ordnance Survey • OS Mastermap • OS Landplan (1:10000) • OS OpenData Vector Map District
Historical maps	Historical Digimap / Ordnance Survey: • Town Plans 1855-1895 (1:500, 1:1056) • County Series 1854-1969 (1:2500, 1:10560 scale) Other maps of undetermined scales (Appendix A) available digitally from local history websites and local studies libraries (http://history.youle.info/maps.html; http://www.sheffieldindexers.com/LinksIndex.html): • Gosling, 1736; Uncredited, 1736; Fairbank, 1771; John Leather Land Surveyor, 1823; Uncredited, 1832; Lt. Robert Kearsley Dawson, 1832; Robert Creighton, 1835; Eric Youle, Growth of Sheffield 1832-1954, 2010.
Street and place names	Edina Digimap / Ordnance Survey • OS Mastermap • Vectormap Local • 1:50,0000 Gazetteer References to water related features: spring, river, brook, bourne, vale, etc.
Citizen science	Elicited from chance encounters with local people, and from web-forums: • Sheffieldforum.co.uk • Sheffieldhistory.co.uk
Other information	Historical written texts: • Numerous historical texts describing the location of Sheffield's springs, watercourses, and water supply system (Addy 1888, Blackwell 1828, Hall 1922, Holland 1824, Leader 1875, 1901, Stainton 1924, Taylor 1879, The London Gazette 1901, White 1837, Woolhouse 1832). • Numerous modern accounts by local and amateur historians (Crossley 1989, Davy 1970, Duncan 2011b, Hey 2010, Olive 2006, Sheffield City Council 2010, Walton 2011). Paintings illustrating Sheffield's old water features (Appendix B), including: • Street Flushing • Crookes Valley reservoirs
Topography	Edina Digimap / Ordnance Survey • OS Landform PROFILE DTM (10m resolution, 1:10000) +/-2.5m vertical accuracy
Geology and hydrogeology	Geology Digimap / British Geological Survey • BGS Geology (1:50000) bedrock and superficial deposit maps. • BGS Hydrology (1:625,000) hydrogeology map • BGS Borehole Record Viewer (scans) The Coal Authority • Pumped groundwater levels have largely recovered since mining activity (pers. comm. September 2011). Other studies: • Hydrogeology descriptions available in various studies (Banks 1997, Banks et al. 1997, Ibrahim et al. 2010, Jones et al. 2000).

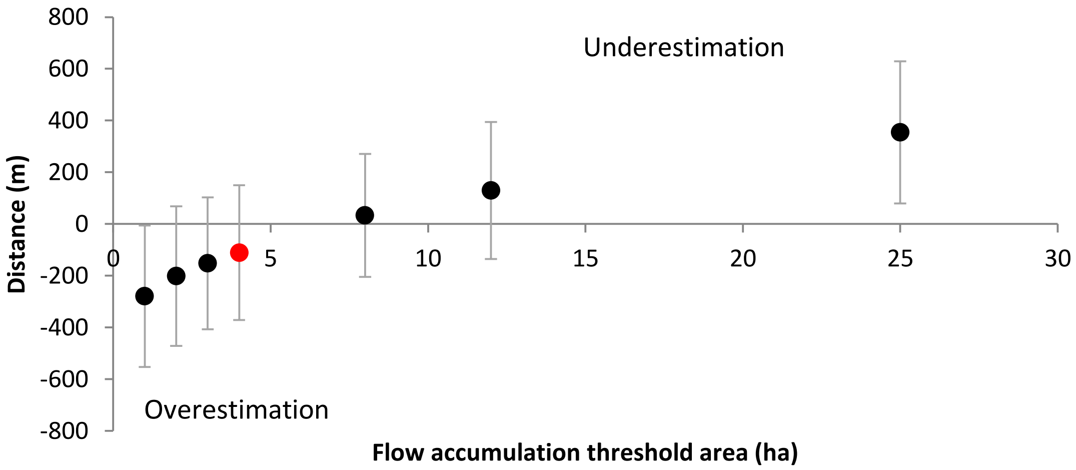


Figure 9 Topographic flowpath training results showing the average distance (with error bars showing standard deviations) between the modelled topographic flowpath stream origins and training points, for seven flow accumulation thresholds as upstream contributing areas. Chosen threshold of 4 ha (i.e. 400 cells) in red.

Table 5 Indicating stream and spring capture: case study data sources and details for the lines of evidence.

Type	Data source and details
Sewer network maps	Yorkshire Water (under IP/data agreement) • Shapefile and attributes differentiating combined, surface water and foul sewers.
Night-time minimum flow methods	Yorkshire Water (under IP/data agreement) (Appendix C) • 27 sewer flow monitoring sites throughout 2011. Dry weather period was identified and an "infiltration-inflow / capture proportion" was calculated (average night-time minimum flow rate during the week as a percentage of average daily flow during the week).
Sewer water balance	Yorkshire Water (under IP/data agreement) (Appendix C) • Clean water supply network and DMA zones mapped onto existing sewer flow monitoring catchments. Just one catchment aligned with a similar inflow area draining through a single sewer outflow monitoring point.
Water chemistry methods	Water typing study (Chapter 4) • 5 sites, 3 of definite capture, 1 of strongly indicated capture and 1 of no capture. Chemistry method was able to differentiate captured flow mixing in sewer.

3.3.3 Results of locating lost streams and springs

In the 89 km^2 search area, 123 km of watercourse are shown on modern maps and 22% of these are underground in culverts (**Figure 10**). Historical maps show 140 km of open watercourse, including some extended lengths of headwater tributaries as well as watercourse segments completely lost from modern records (**Figure 11**).

Topographic flowpath modelling generated a total predicted stream length of 330 km in the search area (**Figure 12**). This is likely to be an overestimation reflecting the chosen flow accumulation threshold to slightly overestimate the channel origins, and because there is a "feathering" effect of multiple flowpath lines in areas of flatter topography. Of the stream segments found from historical maps, 75% are within 10 m of a topographic flowpath line, and 61% intersect or touch a topographic flowpath line. This suggests a good predictive ability of the technique to map lost streams (**Figure 14**). The remaining 25% are at distances of up to 250 m, typically in floodplain areas where flat topography limits horizontal accuracy of channel location, and in one case up to 500 m due to lack of data on the edge of the search area. Acknowledging these sources of potential error, topographic flowpath modelling would provide a suitable "first pass" analysis of likely stream locations that is relatively quick and could allow targeting of more time-consuming searches of historical maps and other lines of evidence.

The lines of evidence were mapped and visually combined to digitise a best available estimate of the locations of lost streams in Sheffield, shown as a map of the predicted original stream network (**Figure 13**). This is inherently subjective, and the quality of the specific evidence at each site must be interpreted on a case by case basis. In general, the historical mapped streams are supported by topographic flowpaths, and other lines of evidence are in proximity to either historical mapped streams or topographic flowpaths. Where historical maps clearly show stream segments, these are nominally given priority, and the topographic flowpaths are used to fill in the gaps. Feathering of multiple topographic flowpath lines is visually filtered and reduced to select a plausible stream route where no precise historical mapped route is available; in such cases, there may be reasonable confidence of the presence of a lost stream, but less confidence in its precise location. Headwaters are typically extended as far upstream as spring location evidence. Difficulties arise when lines of evidence conflict:

- At several locations, topographic flowpaths do not match historical maps. In many cases this is due to flatter topography reducing the reliability of the technique, so historical maps are prioritised. In other cases the historical maps themselves are ambiguous (single meandering lines could be streams or just paths or boundaries), and only if supported by other evidence are they shown as a potential lost stream. For example, while street names indicate a watercourse at Brook Hill, the historical map lines and topographic flowpath locations are unclear, making this lost stream plausible, but not confidently so.
- There is strong evidence from historical texts of springs or streams in locations such as Barker's Pool and Bower Spring (Leader 1901), but no historical maps show watercourse routes from here, and no topographic flowpaths are clearly demarcated in these areas (considerable ground level changes are also likely). In these cases, a plausible line is drawn to connect them to the nearest downstream river, acknowledging the uncertainty. Indeed, Leader (1901) refers to a "vigorous stream" of water coursing down Townhead Street, but this is most likely to refer to street drains that were occasionally flushed with the spring-fed water from Barker's Pool – an artificial drainage network may have long altered watercourse locations.

Given these considerations, **Figure 13** would be best considered a living document, to which further refinements are inevitably possible, but which provides a reasonable map of the plausible locations and extent of Sheffield's lost watercourses. Qualitative confidence in the evidence has therefore been indicatively colour-coded: high certainty indicates watercourses shown convincingly on modern maps or where there is irrefutable evidence or all lines of evidence corroborate each other; low certainty reflects conflicting or just a single line of evidence; the remaining are the best available estimates reflecting more than one line of corroborating evidence but requiring some degree of judgement to draw the connecting route of the watercourse.

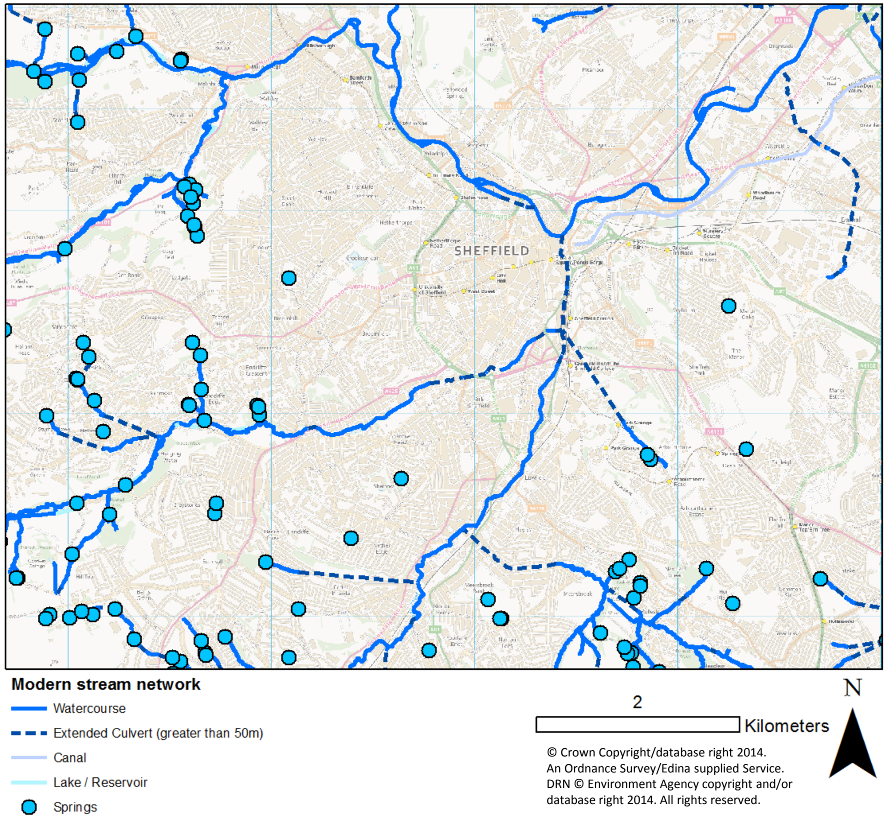


Figure 10 Modern stream network and springs.

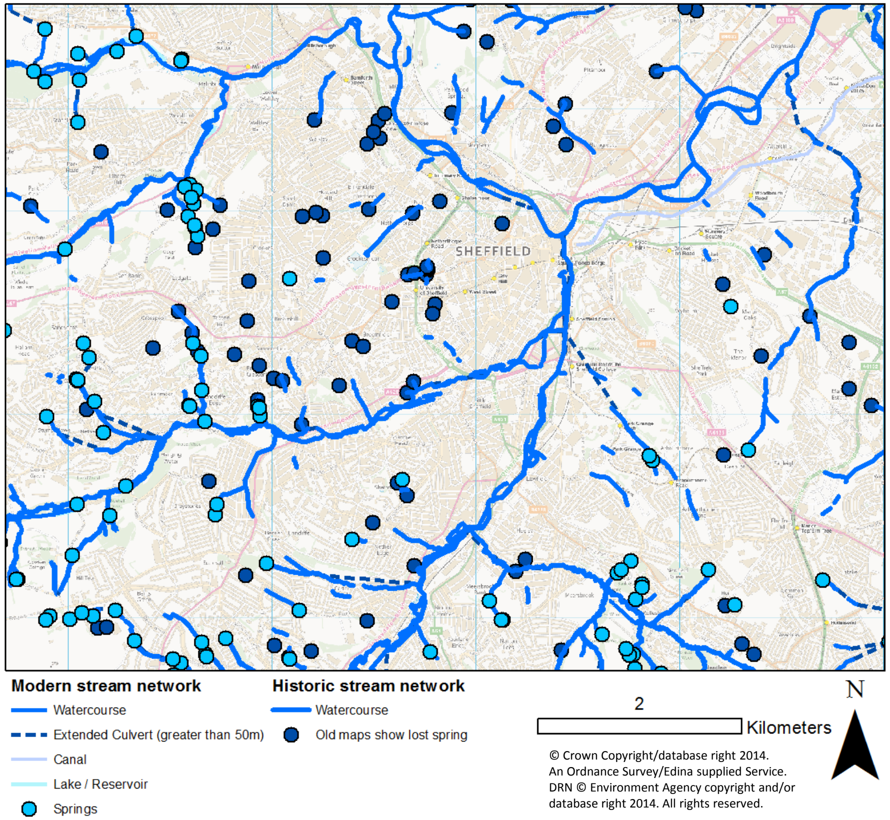


Figure 11 Historical mapped stream network and springs, with modern stream network and springs.

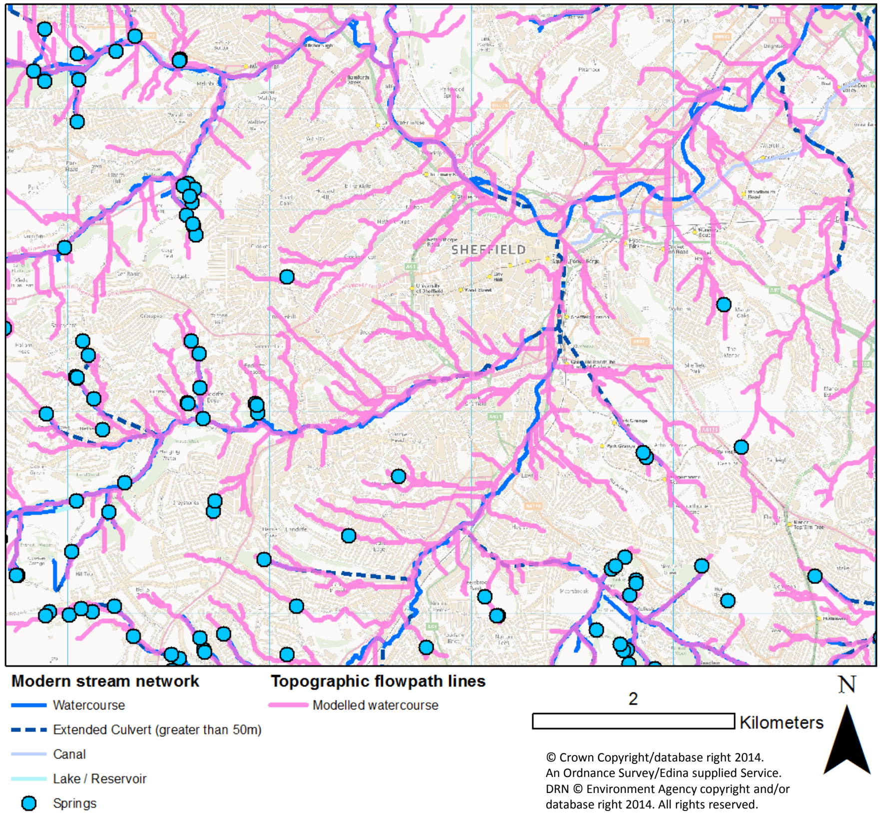


Figure 12 Topographic flowpath lines, with modern stream network and springs.

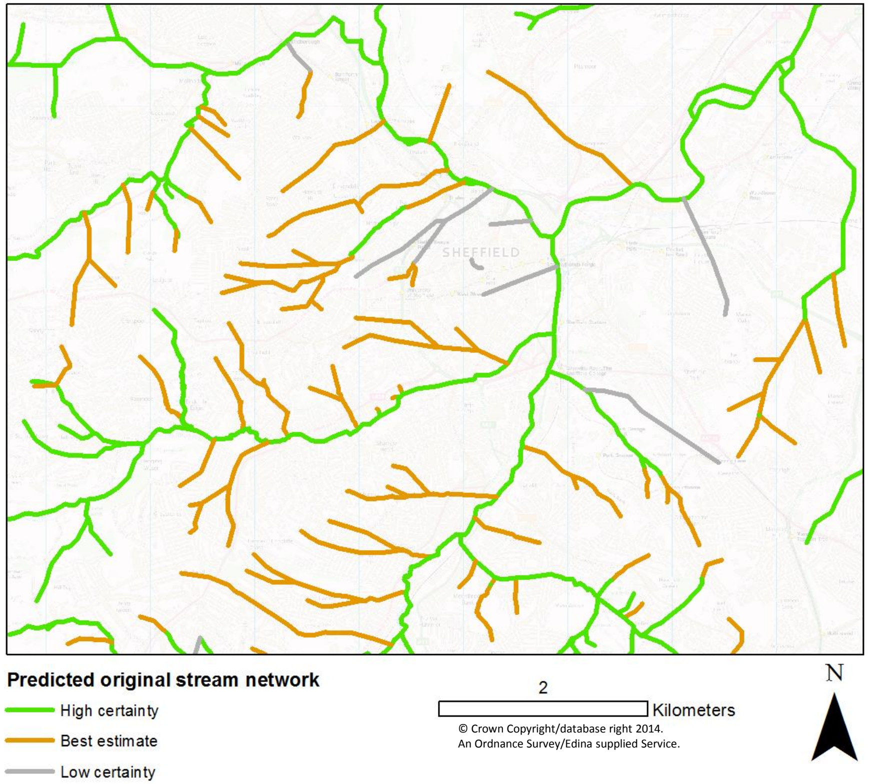


Figure 13 All lines of evidence visually combined to show full stream network, including both existing and lost streams, and colour-coded to reflect locations of low certainty (conflicting or very sparse evidence) and high certainty (streams or culverts definitively shown on modern maps).

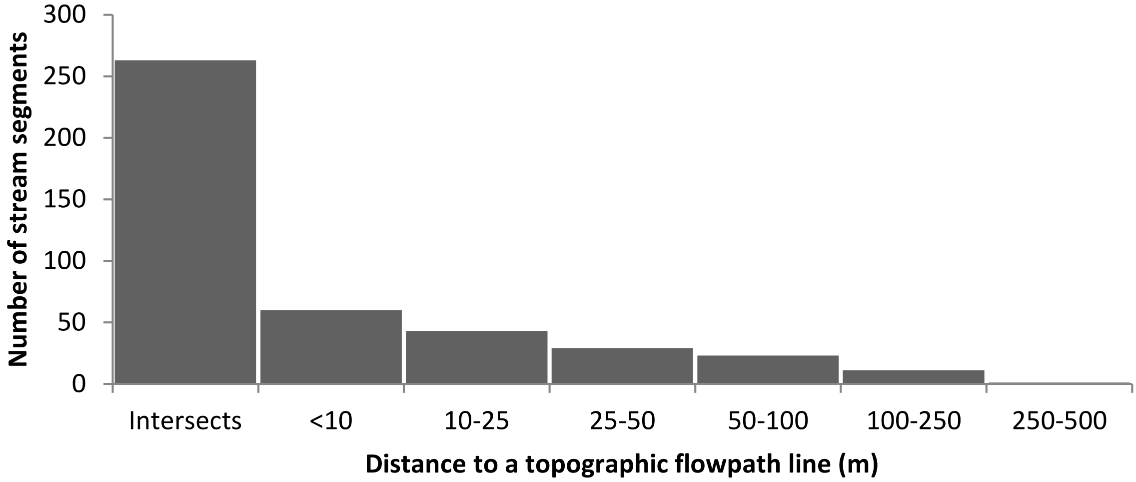


Figure 14 Histogram showing distances of each stream segment marked on historical maps to the nearest topographic flowpath line. The majority touch or intersect the nearest topographic flowpath line.

Modern maps show 149 springs in the search area, and historical maps show a similar number but with a different spatial distribution. There are 119 historic springs shown that are not within 10 m of mapped modern springs, and these are almost exclusively in the dense city centre areas rather than the suburbs. Springs do not visually correlate with either a particular geology or appear at the boundary of mapped geology types, and hydrogeology data are insufficient to determine depth to water table across catchment, reflecting complex geology with multiple shallow aquifers.

Street and place names identified almost 400 references to streams or springs. The 39 contributions of citizen science reports detailing local knowledge of old streams or springs and the 29 references to old streams or springs from other information are predominantly concentrated in the urban centre; bias in the coverage may be explained by greater notability of features in the centre rather than suburbs.

Combining the information visually to produce the best estimate of lost streams (including filtering the overestimated topographic flowpath lines and using references to lost streams to connect historical mapped stream segments) yields a stream network 187 km long. This is an estimated extra 64 km of watercourse missing from the search area that is not recorded as watercourse or culvert today and therefore may be captured. This equates to 52% loss or total burial of stream length in the search area.

3.3.4 Results of indicating stream and spring capture

Visual inspection of the results with sewer network maps ruled out several lost watercourses from being captured because they have been replaced by surface water sewers that flow to a downstream river. In at least seven cases, the sewer network maps show surface water sewers that replaced the lost streams discharging to combined sewers, and this strongly indicates capture by interception. In other cases, capture cannot be confidently determined from the sewer network maps; many other streams or springs have no obvious surface water sewer or culvert to convey their flow and appear to have been replaced by combined sewers (capture by conversion and direct spring capture).

Analysis of the 24 flow monitoring sites showed a significantly higher baseflow in locations where lost streams and springs appear to have been replaced by combined sewers compared to locations where there were no lost streams or springs (student's t-test, $t=2.15$, $df=22$, $p=0.04$) (Appendix C). There is considerable uncertainty due to unresolved data quality issues such as flow meter drift, meter blockage (“ragging”) and data blanks, and to improve confidence in this analysis it would be better to analyse a calibrated hydraulic sewer network model to account for lag times of water from further up the catchment which may be attributed to elevated baseflow.

A water balance was possible for just one site (given the locations of District Metering Zones and sewer flow meters) which corroborated that approximately 40% of the sewer flow was likely to be either infiltration or captured flow (Appendix C). At this one location, it was possible to confirm by site visit that springs were piped into a garden pond then overflowed to a combined sewer.

A major ion and minor ion water typing chemistry study was applied to five sites determined by the capture indication methodology (detailed in Chapter 4). The water typing method was found to successfully detect the mixing of captured streams and springs in some cases where end-points were known, but the geological heterogeneity meant that it was difficult to predict the expected end-points of local streams and springs where they could not be directly sampled. Three sites were direct inflows of capture by interception including an open stream entering a culvert and then discharging to a combined sewer, a culverted stream as a surface water sewer discharging to a combined sewer, and a spring-fed reservoir outfall discharging to a culverted watercourse that is now a combined sewer. In these cases, the capture and water typing analysis was verified by visual confirmation of connectivity. Another site was an example of capture by conversion and direct spring capture, and so connectivity could not be visually verified, though a spring-fed garden pond discharges to the combined sewer. Consequently, the water typing was inconclusive in this site. At the fifth site, there was no indication of stream or spring capture: despite some possible lost streams in the vicinity suggested from historical maps and from street names, sewer network maps and topography suggest they would not flow into the combined sewers tested. At this site the water typing was also inconclusive; the complex geology of this area results in a range of water types that are difficult to predict to interpret the water typing results. However, there were no signs of visual connectivity of any streams into the combined sewers here.

3.3.5 Review of the lines of evidence

Drawing on both the information from lines of evidence review and the experience of applying the data to the case study catchment, each line of evidence was qualitatively assessed for characteristics considered to be important for future application: data availability, the time or resource requirements, and the reliability. The results of this are presented in **Table 6** and **Table 7**.

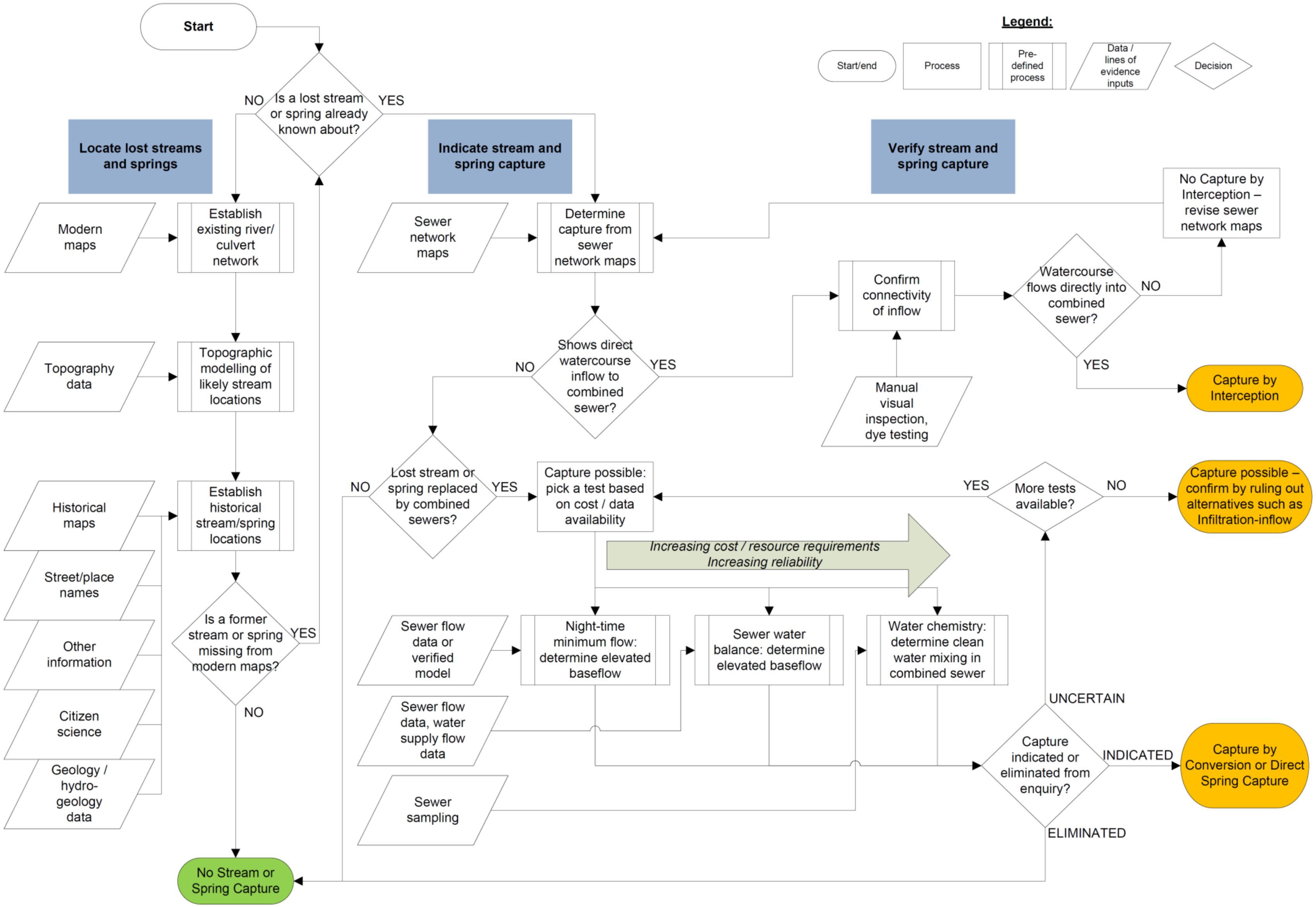
Table 6 Qualitative assessment of lines of evidence available to locate lost streams and springs, based on the review of evidence and experience from case study application. Traffic light colour scheme: green=good; amber=medium; red=poor.

Locating lost streams and springs			
Line of evidence	**Data availability**	**Time / resources**	**Reliability**
Modern maps	Full coverage at range of scales across UK.	Desk-based. Easy, quick vector search by attribute type for current stream network for streams and springs.	Essential to establish known watercourse network, but culvert positions rarely mapped precisely, and many "lost streams" are not mapped at all.
Historical maps	Geo-referenced historical maps available across UK, but map ages and scales limited in spatial and temporal coverage. Generally unavailable prior to urban development.	Desk-based. Time consuming manual raster search across multiple versions. Oldest maps may not be geo-referenced or digitised.	Clearly marks streams and springs in many cases, though can be sometimes ambiguous. Catchment changes can alter location and flow rate of historical springs.
Street / place names	Full coverage of UK street names, though some place names not always labelled on modern maps.	Desk based. Easy, quick vector search of street and place names, though place names from historical maps may require manual search as above.	Names can reflect proximity to current or past water features, but often not precise locations. Can be coincidental.
Other information	Literary or image references available in some cases; likely to be incidental in descriptive pieces. Some books specialise in "lost rivers of…" but tend to focus on larger cities and watercourses.	Desk-based. Time consuming search especially when unavailable in digital searchable libraries. Less likely that information has already been collated outside of larger towns and cities.	References can be ambiguous and lack spatial precision.
Citizen science	Many areas have local amateur history groups. Individuals may have local knowledge but difficult to identify them.	Desk-based. Requires new engagement with public and local historians.	Can identify sites to target search of other evidence. Effective communication essential to avoid misunderstanding, and often difficult to verify claims.
Topography	Full coverage of topographic data at a range of scales across UK.	Desk-based. Easy, quick processing with GIS software for entire catchments. Accurate stream initiation threshold can require field data, but can be estimated.	Most effective in hilly catchments. No historical pre-development topographic data, so urban development and made-ground alter results.
Geology and hydrogeology	Full coverage of geology maps across UK, but not always detailed enough to confidently map springs or groundwater. Groundwater depth data limited in spatial coverage, few verified models available.	Desk-based. Easy, quick processing of geology map data, but complex and time consuming to find and interpret data to determine groundwater depth and spring locations.	Most effective in areas of less complex geology. May be difficult to reliably determine spring locations.

Table 7 Qualitative assessment of lines of evidence available to indicate and verify stream and spring capture, based on the review of evidence and experience from case study application. Traffic light colour scheme: green=good; amber=medium; red=poor.

Indicating stream and spring capture			
Line of evidence	**Data availability**	**Time / resource requirements**	**Reliability**
Sewer network maps	Good coverage across the UK for sewered catchments, but attribute data (size, age, material etc.) very limited.	Desk-based. Easy, quick interpretation in GIS of lost stream and spring proximity to combined or surface water sewers, and of apparent direct watercourse connections to combined sewer.	Essential data, but reliability can be poor with regard to sewer characteristics, connectivity, and precise locations.
Night-time minimum flow methods	Often no prior data: may require sewer flow monitoring or existing verified hydraulic model.	Site investigation or desk-based. Considerable time and resources for data collection. However if data already exist, analysis is relatively quick and easy.	Various techniques to analyse flow data, but difficult to differentiate stream and spring capture from other baseflow sources such as infiltration-inflow.
Sewer water balance	Often no prior data: may require sewer flow monitoring or existing verified hydraulic model. Water supply data available in metered zones, but few catchments fully metered at household level.	Site investigation or desk-based. Considerable time and resources for data collection. However if data already exist, analysis is relatively quick and easy.	In most catchments, estimates of sewer flow, water supply flow, and other losses are required, reducing estimate of clean baseflow. Difficult to differentiate stream and spring capture from other baseflow sources such as infiltration-inflow.
Water chemistry methods	No prior data: requires samples from network. Sample locations can be limited by accessibility. May be difficult to sample lost streams and springs if location unknown.	Site investigation. Requires a person to sample at day and night; alternatively, autosampling equipment available but costly. Requires laboratory analysis.	Multiple techniques available including individual markers, pollutant hydrograph (individual markers combined with flow data), or water typing. Potential to reliably differentiate mixing of clean waters with wastewater, though applicability reduced where sample site access is constrained.
Verifying stream and spring capture			
Connectivity testing	Unlikely to be prior data: requires individual on-site investigation. Inapplicable to capture by conversion or direct spring capture if source of inflow cannot be identified.	Site investigation. Easy, quick connectivity determination by visual inspection or dye testing. However, requires a person for site-investigation. Requires suitable sites to be identified through other means.	Potential to reliably confirm capture by interception by verifying direct inflow of a watercourse.

Figure 15 (Overleaf) Capture indication methodology flowchart.



Start
Is a lost stream or spring already known about?
NO
YES
Locate lost streams and springs
Indicate stream and spring capture
Verify stream and spring capture
Legend:
Start/end
Process
Pre-defined process
Data / lines of evidence inputs
Decision
Modern maps
Establish existing river/ culvert network
Sewer network maps
Determine capture from sewer network maps
No Capture by Interception – revise sewer network maps
Topography data
Topographic modelling of likely stream locations
Shows direct watercourse inflow to combined sewer?
NO
YES
Confirm connectivity of inflow
Watercourse flows directly into combined sewer?
NO
YES
Capture by Interception
Manual visual inspection, dye testing
Historical maps
Establish historical stream/spring locations
Lost stream or spring replaced by combined sewers?
NO
YES
Capture possible: pick a test based on cost / data availability
More tests available?
YES
NO
Capture possible – confirm by ruling out alternatives such as Infiltration-inflow
Increasing cost / resource requirements
Increasing reliability
Street/place names
Other information
Citizen science
Geology / hydro-geology data
Is a former stream or spring missing from modern maps?
YES
NO
Sewer flow data or verified model
Night-time minimum flow: determine elevated baseflow
Sewer water balance: determine elevated baseflow
Water chemistry: determine clean water mixing in combined sewer
Sewer flow data, water supply flow data
Sewer sampling
UNCERTAIN
Capture indicated or eliminated from enquiry?
INDICATED
Capture by Conversion or Direct Spring Capture
ELIMINATED
No Stream or Spring Capture

3.4 Towards a procedure: capture indication methodology

For users in the water industry wanting to assess where stream and spring capture occurs, knowing which lines of evidence to use or to commission, and in what order, will be informed by issues such as data availability, the time and resource requirements of each line of evidence, and the potential reliability or confidence of each test. Drawing on experience from this case study application and from the qualitative assessment (**Table 6** and **Table 7**), a multiple lines of evidence approach is presented as a procedure in a flow-diagram (**Figure 15**). This will now be described and discussed.

To begin with, the locations of lost streams and springs are determined using desk-based evidence in GIS. The approach is to determine the known stream and river network, and then identify missing or "lost" water features. Given the good accuracy of the topographic flowpath modelling achieved in this study, this is recommended first to target application of other lines of evidence (such as historical maps or citizen science) that may be more time-consuming, have limited spatial precision, data availability or coverage, or may require public engagement. Streams and springs still visible or connected to the known modern river network can be eliminated from enquiry. Each additional line of evidence corroborating the possibility that a former stream or spring is no longer visible or connected to the modern river network strengthens the likelihood that it is lost and a candidate for capture.

The next stage is to indicate where lost streams and springs may have been captured into combined sewers. Sewer network maps should be used first, as a widely available data source for a quick desk-based assessment. They can be used to determine where a lost stream (either as a surface water sewer or culvert) appears to flow directly into a combined sewer, suggesting capture by interception. This could then be verified by commissioning a site investigation to determine the connectivity in the field; it is possible that the sewer network data are incorrect and should be revised.

Sewer network maps can also be used to determine where the located lost streams and springs appear to have been replaced by combined sewers. Where there are surface water sewers that flow to a downstream river, capture can be ruled out. Where there are no alternative flow routes other than the combined sewers, then it is possible that the lost stream or spring is captured. Further lines of evidence or tests can be commissioned to improve confidence in the assessment. Where flow data or a verified hydraulic sewer flow model exist for the network, a desk-based based study of night-time minimum flow or a sewer water balance is recommended for relative ease. These lines of evidence can indicate the presence of elevated baseflow, though they may not be able to differentiate this from infiltration-inflow through pipe cracks and defective joints. If further confidence is required, water chemistry methods may be commissioned; though more costly in time and resources, they may corroborate other lines of evidence and may be able to differentiate captured flow from infiltration-inflow in some circumstances. Where the results of these are still uncertain, it is not possible to further verify capture by conversion or direct spring capture because there may be no discrete inflows. Instead, it is recommended to rule out other sources of clean water in the sewer, such as infiltration-inflow or mains water supply pipe leakage; this may be directly observed as leakage through sewer pipe cracks and defective joints using CCTV and other techniques outlined elsewhere (UKWIR 2012).

3.5 Discussion

Application of the capture indication methodology to a case study catchment has identified many lost streams and springs across Sheffield. While some of these may be hidden headwaters of known watercourses, many are entirely lost, unrecorded in modern maps, and may have been dewatered or captured into combined sewers. Other studies that have mapped stream burial previously have relied on topographic flowpath modelling (e.g. Bishop et al. 2008, Elmore and Kaushal 2008) or just historical maps (e.g. Galster 2012). Experience in this study suggests that neither is capable of infallibly detecting all lost streams and springs: topographic flowpath modelling is less accurate in areas of flatter topography or where made-ground in urban areas has infilled former valleys; historical maps may have limited spatial or temporal coverage and interpretation can sometimes be ambiguous. Use of the additional lines of evidence provides greater confidence in locating lost streams and springs, and should be considered in other studies mapping stream burial.

In the case study catchment, 52% of the stream network by length has been culverted or lost entirely, which is similar to findings elsewhere in the literature. Metrics used in some other studies make direct comparison difficult, but Elmore and Kaushal (2008) found that

66% of streams in Baltimore City had been buried, increasing with urbanisation and with decreasing stream size. There are no known comparable studies of stream burial in the UK.

This study is the first to detail a methodology to indicate where lost streams and springs are captured into combined sewers. Despite some other examples of stream and spring capture (including management of it) such as Zurich or Pittsburgh, Chapter 2 found that none had detailed a methodology, making comparison difficult. The finding of several sites where capture by interception, capture by conversion or direct spring capture occurs does support the distinction of these three separate types of capture, which require different lines of evidence to indicate and verify. While some lines of evidence have not been possible to fully examine due to data availability, the general approach of each has been demonstrated in this study.

The study has demonstrated that streams and springs are captured into Sheffield's combined sewer system and are flowing to the WwTW. Further application of the lines of evidence in this study would enable a thorough quantification of the number of captured streams and springs in this case study catchment, the volume of clean baseflow they contribute, whether these sewers are at risk of capacity-related problems such as sewer flooding, surface water flooding or CSO spills. The costs, benefits and feasibility of management options such as separating the captured streams and springs through daylighting and restoration of watercourses could then be explored, drawing on the experience from Zurich.

Further development of this methodology is recommended. First, application to new case study catchments would explore the effectiveness of the lines of evidence in different scenarios. For example, anecdotal reports suggest that watercourses have been converted into combined sewers in Hull as recently as the 1960s (Steve Wragg, Hull City Council, pers. comm. March 2013). It would be useful to test this methodology here because, unlike Sheffield, Hull occupies flat former coastal marshland with a history of extensive land drainage that may hinder topographic flowpath modelling. A collaborative research project with water companies across the UK would enable access to data that has not yet been available in this study, as well as providing an insight into the extent and prevalence of stream and spring capture in towns and cities.

Second, this methodology could be developed as a modelling framework. Currently, the procedure flowchart (**Figure 15**) assumes equal importance of each line of evidence, when in practice each have strengths and weaknesses. The qualitative assessment of the lines of evidence identified the relative strengths and weaknesses of the evidence with regards to data availability, times and resource requirements, and reliability. Chapter 5 develops a predictive tool using a Bayesian Belief Network (BBN) to enable users in the water industry to predict the likelihood of stream and spring capture across entire sewer networks. The BBN uses expert knowledge to integrate the desk-based lines of evidence and evaluate their importance, enabling the user to target and prioritise sewers for those lines of evidence that may involve considerable cost or effort through data collection and site investigation.

3.6 Conclusion

This chapter has demonstrated a multiple lines of evidence approach to indicate where lost streams and springs may be captured into the combined sewer system. In a UK case study catchment, it found that over half the stream length is lost or buried, and confirmed that there are at least five sites where streams and springs flow into combined sewers to the WwTW. This is worthy of further attention by the water industry to now examine the full costs and impacts of this, and the opportunities for management.

Combining multiple lines of evidence is recommended to address uncertainty associated with individual lines of evidence. By first locating lost streams and springs, then indicating where capture may occur, and then attempting to verify this, relatively simple desk-based information can be used to target and justify the further confirmatory (and expensive) methods. There is scope to integrate this methodology into a predictive tool that will allow a network wide assessment of capture to help to target these confirmatory methods. There is also scope to test the methodology on other case studies, and develop a partnership with the water industry to trial particular lines of evidence that were not possible to fully explore in this study.

4 Water typing for detection of captured streams and springs in combined sewers

4.1 Introduction

Some watercourses historically buried under towns and cities into culverts have also become lost by having been intentionally "captured" into combined sewer systems. They now flow to wastewater treatment works (WwTWs). A well-known example is the River Fleet in London, which was purposely converted into a combined sewer and diverted into the Victorian high-, mid- and low-level interceptors, adding to the wastewater baseflow. Ancient springs along its course have also been drained into the sewers (e.g. Myers 2012). While the principle of stream and spring capture is acknowledged in a few well-known examples like the River Fleet, there has been little consideration by the water industry of the extent, location or quantity of stream and spring capture in combined sewer networks, and what the consequences and costs of this are (Chapter 2).

There has been considerable focus on the unintentional infiltration-inflow of groundwater through sewer pipe cracks and defective joints (UKWIR 2012) and the rainfall-derived surface runoff inflows to combined sewer systems (UKWIR 2009, Zhang 2007). These can essentially be the same waters as captured streams and springs, but represent a different entry mechanism and cause (Chapter 2). Measures to rehabilitate combined sewers by waterproofing or to reduce stormflow inputs using sustainable drainage systems will not tackle the historic, intentional capture of streams and springs.

Like infiltration-inflow, stream and spring capture increases the clean baseflow into the system, reducing sewer capacity, increasing sewer flood risk, and increasing wastewater treatment costs (Chapter 2). It also represents a host of negative environmental, social and economic effects associated with the burial of urban watercourses (Broadhead and Lerner 2013, Elmore and Kaushal 2008, Everard and Moggridge 2012, Freeman et al. 2007, Roy et al. 2009, Stammler et al. 2013, Wild et al. 2011).

Even if we know where lost streams and springs once used to flow, their connectivity into combined sewers cannot be assumed, because there may be unmapped culverts taking the flow instead of a combined sewer, and in some cases hydrological changes may have dewatered springs. There is therefore a need for direct, in-sewer detection of the captured waters mixing with wastewater. Existing methods used to detect groundwater infiltration-inflow may present difficulties when applied to captured streams and springs:

- **Water balance methods** – indirect indication of infiltration-inflow by comparing the volumes of sewer flows from an area to the tapwater inflows to the area. This can be used where there are data from domestic water meters and from sewer flow monitoring, and has been attempted at entire catchment scales (e.g. Hajnal 2008, Kim et al. 2001). Because it relies on assumptions about water use and losses, it can be imprecise in practice, and not possible for many non-metered sub-catchment areas (UKWIR 2012).
- **Sewer hydrograph methods** – equating the night-time minimum flow (where domestic wastewater inputs are at their lowest) to infiltration-inflow, capture or other baseflow is a widely used technique (Metcalf and Eddy Inc. et al. 2004). Research has developed these estimations with consideration of the hydrograph recession curves following storms (e.g. Wittenberg 1999, Wittenberg and Aksoy 2010, Zhang 2007), showing that infiltration-inflow seasonally varies and has both fast and slow responses to rainfall events. Sewer network modelling will often use a constant infiltration-inflow estimate, such as 10% of the dry weather flow, to calibrate modelled flows to observed flows after calculating expected domestic and trade wastewater inputs (Butler and Davies 2011). The method requires installation of flow monitors, and it is unlikely to differentiate captured flow from infiltration-inflow once mixed in the sewer.
- **Chemical markers** – there are no obvious single chemical markers unique to captured waters and thus not present in wastewaters, but studies have used Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), conductivity and temperature sensing to indicate the ingress of infiltration-inflow (UKWIR 2012). Stable isotope ratio methods have been proposed to identify a unique chemical fingerprint of infiltration-inflow in combined sewers (Kracht et al. 2007).
- **Pollutant-hydrograph methods** – combining a chemical marker (typically COD, but also stable isotopes) with the hydrograph method to produce a mixing model of pollutant loads and wastewater flows. Some studies have developed in-situ proxy

evaluation of pollutants such as COD using ultraviolet-visible spectroscopy (UV-VIS) techniques; coupled with flow monitors, this can capture continuous data enabling a robust evaluation of infiltration-inflow. This assumes a baseline chemistry of infiltration-inflow, e.g. 0 mg/L COD, giving rise to potential uncertainty if applied to captured streams or springs which may have been contaminated.

A widely used approach in hydrogeological studies is the use of major ions to differentiate groundwater types mixing in aquifers (e.g. Hutchins et al. 1999, Navarro and Carbonell 2007, Peeters 2014, Rains et al. 2006). Major ions are ubiquitous in waters, generally conservative and easily analysed. It is not their presence or absence but relative proportions of interest, clustering into specific groups (or water "types") based on their dominant chemical constituents, which for many natural waters reflect their parent geological material (Freeze and Cherry 1979, Güler and Thyne 2004, Lakshmanan et al. 2003, Rains and Mount 2002). This could be a useful technique to detect captured streams and springs, complementing the other methods identified above and addressing some of their limitations.

The aim of this study is to test whether major ion water typing and analysis of minor ions and trace metals can be applied to detect captured streams and springs in combined sewers, using sites in Sheffield, UK, through the following hypotheses:

1. wastewater and captured waters are distinctively different water types, which are identifiable amid the short-term variability in water chemistry (especially that of the wastewater);
2. the wastewater types predominantly reflect the local tapwater type, and the captured waters predominantly reflect the local groundwater and spring chemistries; hence these can be used to "type" the end-points to assess mixing;
3. downstream of stream and spring capture, sewer chemistry reflects mixing between distinctive end-point water types of wastewater (diurnally varying) and watercourse/groundwater (no diurnal variation), tending towards the watercourse/groundwater type during the night-time minimum;

4. major ion water typing results are corroborated by minor ions and trace metals (some primarily associated with anthropogenic wastewater inputs, others with natural geologic inputs) and COD tracing.

This study focuses on stream and spring capture, but the applicability of the method to detect infiltration-inflow is also briefly discussed.

4.2 Method

The general approach to this project has been to characterise springwater and tapwater types in the Sheffield area and then to conduct a sewer capture sampling programme. Springwater types were characterised to identify whether the chemistry of springwaters is similar to captured waters from nearby or from similar geology, in order to predict the expected end-point water type of a captured stream or spring where it is not possible to sample it directly. Tapwater types were characterised to identify how similar tapwater is to the local wastewater chemistry, in order to predict the expected end-point water type of wastewater where it is not possible to sample it directly without the influence of infiltration-inflow or captured water too. The sewer capture sampling programme then tested the water typing method on sites of stream and spring capture in combined sewers. The site selection and sampling methodology are described for each, followed by details of general sample handling, analytical procedures and methods of interpreting water types.

4.2.1 Springwater characterisation sampling programme

Sheffield is situated predominantly on Coal Measures geology, which consists of alternate series of siltstones, mudstones and shales with bands of sandstone. The Coal Measures contain bands of coal and additional minerals not generally reported within the Millstone Grit geology that underlies the Peak District on the western edge of the city. In the Sheffield Coal Measures, extensive historical coal mining has lowered the water table, and the main deep groundwater sources are thought to be approximately 100 m below the surface in many areas based on local borehole records. Springs are therefore localised shallow groundwater sources, recharged through water percolating into the sandstone strata, and discharging at the surface as springs or seeps at the boundary with the lower permeability siltstones and mudstones. The location of springs is therefore difficult to predict due to the relatively low resolution of geological surveys (geology maps do not differentiate the detailed location of the sandstones, siltstones, mudstones and shales within the Coal Measures strata). Springs are therefore not always at mapped bedrock geology boundaries.

Many springs, especially in the dense urban centre, are no longer available to sample, having been covered by development and potentially captured into the combined sewer system. It is possible that springs have been dewatered through catchment changes to their recharge area, such as the development of impervious urban surfaces, but several springs in the city are still flowing, and there are numerous reports of springs flooding basements. Indeed, other studies have shown generally that urban recharge can still be considerable (Lerner 2002).

The chemical signature of Sheffield's springwaters is expected to show the evolution of rainwater and surface runoff recharging through the shallow aquifers. Given the spatially complex geology, the chemical signatures could reflect the geochemical composition of numerous rock types, in addition to the local soil types and urban contaminants.

Thirteen sites of springs, issues and seeps were sampled in and around Sheffield in both rural and urban areas, and from both the Coal Measures and Millstone Grit geological formations. Samples were taken in April 2012, with selected sites resampled to test for temporal variation during a dry weather period in June 2012. These samples represent shallow groundwaters of Sheffield. Samples from each site are detailed in **Table 8** and mapped in **Figure 16**. Samples were collected in a syringe rinsed three times in the flow before being pushed through 0.45 µm filters in the field, stored in a cool box for returning to the laboratory, analysed for pH, and refrigerated for later analysis within one week. Results were compared against the few existing studies of the area's deep and shallow groundwater chemistry (Banks 1997, Jones et al. 2000).

Table 8 Springwater sample site details and descriptions.

Site	Sample	Geology	Qualitative assessment
1	A – Seep, from beneath rocks B – Seep or drainage, rock tunnel under path	Coal Measures	A – Substantial flow within 20 m of seeps. Sandstone to shale bands noticed in cutting. May be contaminated by organic material. May be sports field drainage. B – Contributes to large open boggy area leading to stream. Small flow from beneath path. May be contaminated by mud. May be sports field drainage.
2	A – Spring, from and behind clay pipe	Coal Measures	A – Substantial flow from steep wooded hill slope and steep gully. Sample taken from behind piped flow. Shaley to muddy rocks. May be contaminated by urban area and road above wood.
3	A – Issue, standing pool	Coal Measures	A – Wetland with raised pool of standing stagnant water, forming substantial stream within 10 m of start, but no clear inflow pipe. May not be fresh. May be drainage from cemetery, estates and roads.
4	A – Issue, stream B – Seep, standing water C – Seep, gully	Coal Measures	A – Substantial stream flowing from golf course, so may have modified drainage. May be contamined by rubbish and leaf litter. B – Wet patch forming small stream within 25 m, sourcing from golf course, so may have modified drainage. May be contaminated as standing puddled water. C – Slope gully in woodland collecting water, with small flow at path. May be contaminated by sediment picked up and possible filter problem. Hydrologically disconnected from golf course catchment.
5	A – Seep, exposed	Coal Measures	A – Small seep from hillside towards infilled gully which may use to have issues on hydrological path. Shallow soil, and flow from rocks. May be contaminated by surface runoff from surrounding ground, urban area and road.
6	A – Surface drainage, from clay pipe	Coal Measures	A – Piped surface drainage to stream. Possible groundwater infiltration or soil drainage component due to minimal prior rainfall. May be contaminated by pipe and by misconnections and polluted urban runoff.
7	A – Issue, from plastic/metal pipe B – Issue, gully drainage C – Issue, from clay pipe D – Seep, from beneath rocks E – Issue, from base of rock wall	Coal Measures	A – Issues from back of gardens. May be related to issue/sink further upstream. May be buried beneath gardens and mixed with soil water garden drainage. Possible contamination by pipe and garden and road runoff. B – Issues as surface water from back of gardens in small open dry gully, with deep leaf litter. May be mixed with soil water garden drainage. Possible contamination by garden and road runoff. C – Small piped flow into drainage gully. Orchard upstream of here suggests may be soil drainage, or connected with nearby garden drainage. D – Seep from beneath rocks in gully, forming wet area then sinking to contribute to nearby stream. Possible soil water, but likely shallow groundwater due to rocks here. E – Main issue at base of rock wall behind which is raised meadow. May be drainage or soil water. May be contaminated by leaf litter and may have been pooled.
8	A – Spring, exposed seep B – Spring, from rock	Millstone Grit / Rivelin Chatsworth Grit (Superficial head)	A – Spring contributing to fast peaty stream. Rock outcrop not accessible, but seeps from sphagnum moss area. Possibly collecting surface water following recent rain, or boggy soil water, but visible uprising of groundwater. Possible contamination by sphagnum moss and peat soils. B – Substantial spring discharge from between rocks, leading to large boggy area.

Site	Sample	Geology	Qualitative assessment
9	A – Spring, from rock B – Spring, from rock C – Spring, from rock D – Seep, from beneath rocks	Millstone Grit (Superficial head)	A – Substantial flow from beneath rocks forming small incised gully flow. Boggy area nearby, but distinctive sample. B – Substantial flow cascading from rock area. Possible contamination by leaf litter and lichens, but leaves cleared and pools allowed to refresh. C – Same as above, but from different side of spring. D – Boggy area beside spring, with flow from beneath rocks. Possible contamination from substantial muddy sediment and matted organic matter.
10	A – Seep, wetland B – Issue, from beneath rocks	Millstone Woodhouse Grit	A – Wetland above river level, forming several small draining flows. May be collecting surface water or soil water, or shallow groundwater contribution. Possible contamination by main road, organic matter, and pooling in sunlight. B – Small flow coming from beneath rocks, leading into relatively dried gully. May be contaminated by local field drainage, but appears hydrologically disconnected from this, so likely soil water (reinfiltrated surface drainage) or shallow groundwater.
11	A – Spring, from rock B – Spring, from plastic pipe C – Spring, from beneath rocks D – Issue, from clayey hole E – Issue, from beneath rocks F – Issue, from beneath rocks	Millstone Grit	A – Substantial spring discharge, but may be also reinfiltrated soil water from upstream springs and runoff. B – Substantial spring discharge, piped outfall to spring (11C). May be reinfiltrating surface water and soil water, but likely majority groundwater from rocks. May be contaminated by algal growth in plastic pipe and prior exposure to sunlight. C – Substantial spring discharge from beneath rocks on muddy bed, then pooling and flowing into pipe.). May be reinfiltrating surface water and soil water, but likely majority groundwater from rocks. D – Small flow from hole on top of clayey layer. May be soil water from wooded area. May be contaminated by mud and sediment. At same level as but hydrologically disconnected from nearby springs. E – Small flow from rocks, above nearby issue. Slightly muddy. May be contaminated by muddy sediment. F – Upstream gully with muddy base, but flow only some way down, before forming small intermittent stream. Small flow from beneath rocks. May be contaminated by leaf litter and pollution.
12	C – Spring, from plastic pipe	Coal Measures	C – Substantial flow from plastic pipe, visibly clear of algal growth. Reported spring flow, but may be surface flowing above this. May be soil water also. May be contaminated by pipe and urban recharge and gardens.
13	A – Issue, from pool B – Issue, from pool	Coal Measures	A – Small flow from beneath sandstone type rocks onto clayey soil, forming small shallow gully that soon sinks. Sample from pool that was refreshed, but possibly long residence time and sediment. Likely to be groundwater, but unusual position suggests could be mains leakage or field drainage, or mixed with soil water and surface runoff. May be contaminated by park drainage and chemicals. B – Same as above, but from part of pool that had apparently uprising water.

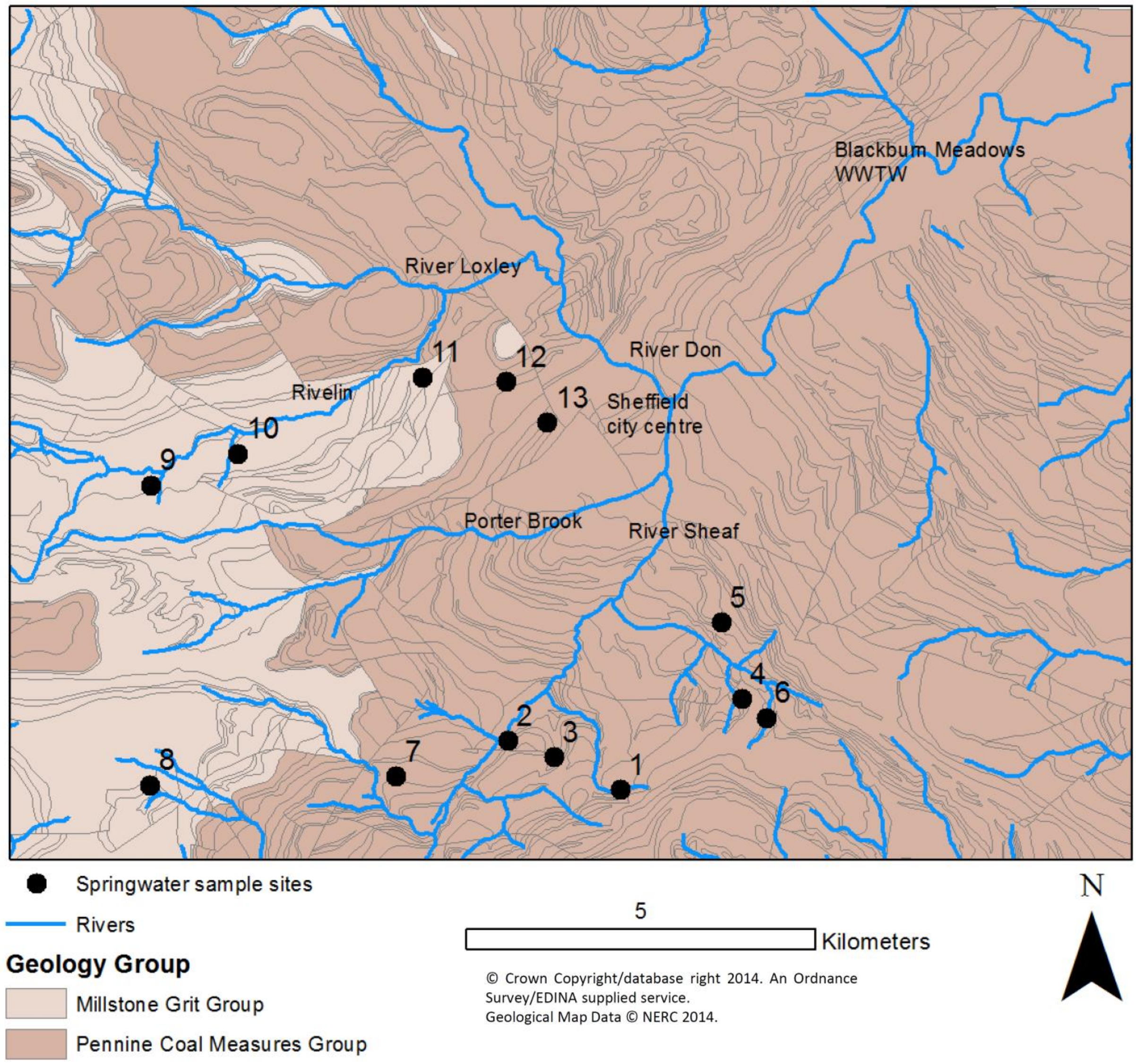


Figure 16 Site map of springwater sample locations and geology groups.

4.2.2 Tapwater characterisation sampling programme

Sheffield's drinking water supply network is divided into distribution areas termed Water Supply Zones (WSZ), which each represent a different blend of source waters. Most water is sourced from reservoirs on the Peak District in Millstone Grit geology, but is blended with imported waters from other parts of Yorkshire Water's network.

Twenty one samples of domestic tapwaters were taken from across Sheffield, covering all WSZs (**Figure 17**). Samples were taken on the 13th July 2012 by volunteers at their homes and delivered to the laboratory in the morning. They were instructed in sample collection from their kitchen tap based on published guidance (Bartram and Ballance 1996).

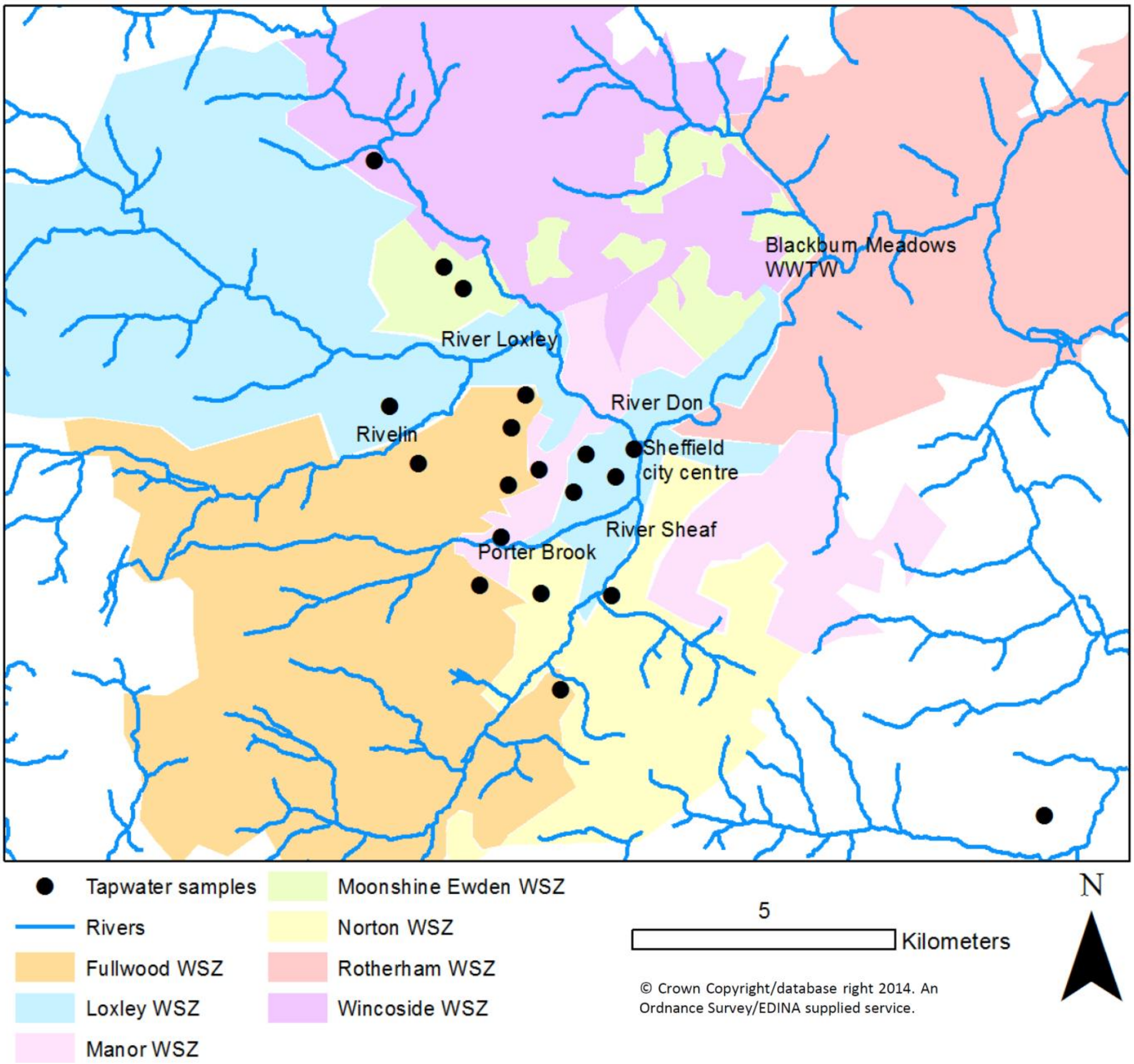


Figure 17 Site map of tapwater sample locations and Water Supply Zones (WSZs).

Volunteers recorded the property postcode (to map the sample and identify the local WSZ), property type and age, the time sampled, time received at the laboratory, and any problems encountered. Samples were analysed for pH, and refrigerated for later analysis within one week.

4.2.3 Sewer capture sampling programme

Site selection

There are numerous streams and springs in Sheffield that, according to multiple lines of evidence, have been captured into the combined sewers (Chapter 3). Five sites (PW, SR, HB, CV, BS) were chosen for this study (detailed in **Figures 18-22)**. These sites were selected as being the most confident examples of capture from all the possible capture sites, i.e. with strong and convincing evidence that a lost stream or spring was entering the combined sewer, and in most cases that could be verified in the field. The second consideration was that a range of capture types be tested: straightforward capture where all end-points may be easily sampled; or where the evidence for lost streams or springs is convincing but where the end-points are unavailable to sample; or one case where capture is unlikely to be occurring. The third key consideration was the location of sample sites; after the first week focusing solely on site PW (to develop confidence in field methods and allow contingency for problems), sites were paired in the following sampling weeks, and needed to be close enough to drive quickly between points to enable samples to be taken within the time periods. A fourth important consideration was the availability of sampling points at each site – an exploratory field visit confirmed that manholes were able to be lifted in all desired locations and that these would not require road closures due to manhole positions. This final point primarily influenced the choice of sampling points at each site, rather than the choice of sites themselves.

Some capture sites (PW, CV, HB) are discrete inflows where a stream is intercepted by a combined sewer, and connectivity can be confidently confirmed visually or by dye testing. At site SR, evidence suggests capture is by conversion (a watercourse has been "replaced" by a combined sewer) and direct spring capture (deliberate drainage of springs into combined sewers); as discrete inflows are not clearly identifiable, the end-point chemistries of inflowing captured water cannot be easily determined. At site BS there is no evidence of capture, but one sample point could contain infiltration-inflow, and this site therefore represents a control.

Between two and four sampling points were identified for each of the five sites, typically including the combined sewer upstream and downstream of the suspected watercourse inflow, and the watercourse inflow itself. The sample points were chosen to be able to characterise the wastewater and captured water end-points individually, but this was not always possible as locations were heavily constrained by accessibility of manholes. Single spot samples were taken at discretion from other points of interest at each site..

For each site, predictions are made from the local tapwater and springwaters of the expected water types in the sewers (**Table 9**). The table also summarises the night-time minimum flow (as % of daily average flow), derived from data supplied by Yorkshire Water of a network flow monitoring programme, using a dry weather flow period in 2011. The night-time minimum baseflow, where wastewater inputs are at their minimum, is attributed to infiltration-inflow (this could also be stream and spring capture where relevant) and thus elevated values suggest a greater input of this water.

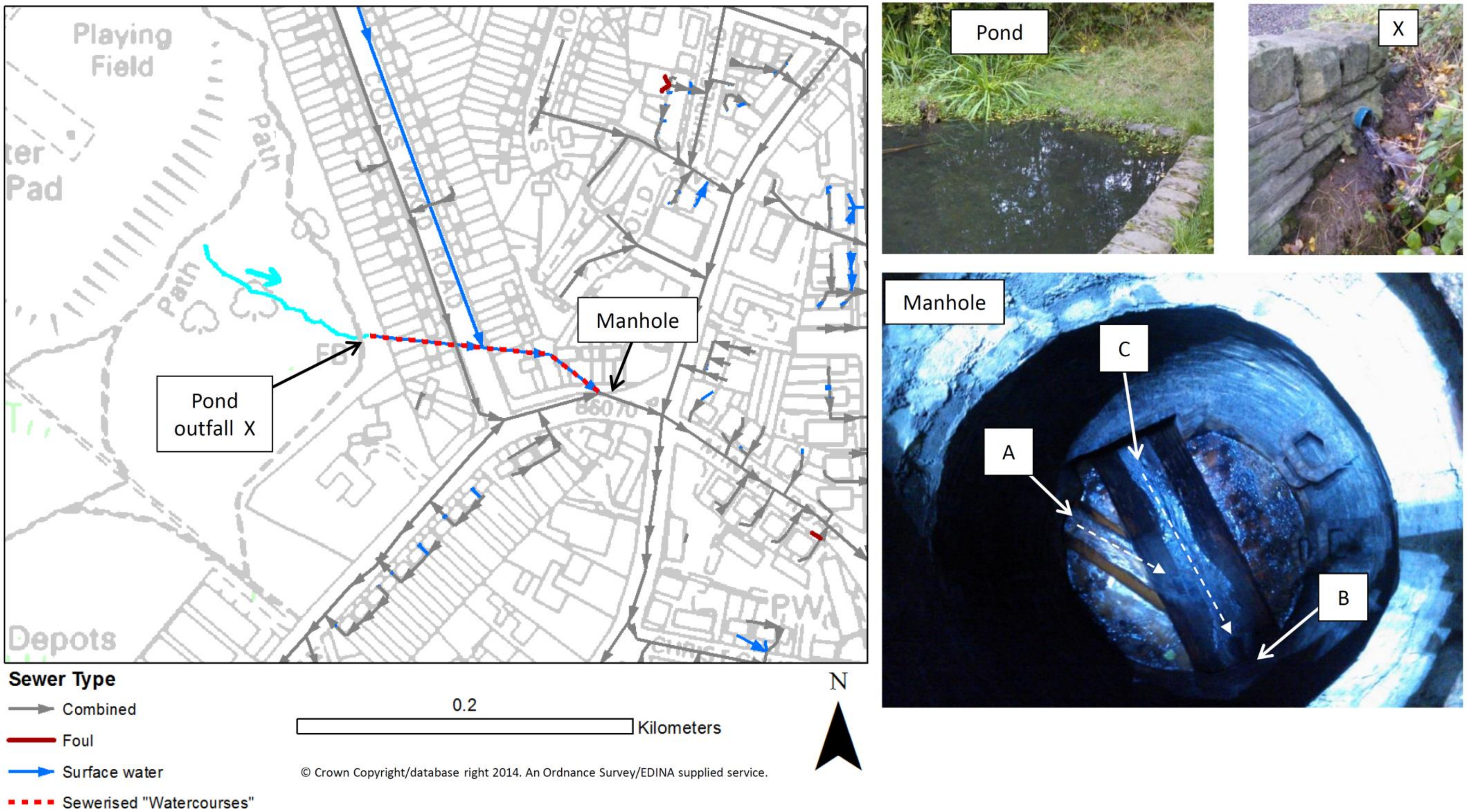


Figure 18 Sewer capture sample location map and pictures for site PW. A small watercourse rises from a spring in a park, forms a pond (sample point X, inset photographs), then flows into a sewer designated for surface water but which is actually a sewerised watercourse. This is intercepted by a combined sewer, and samples are taken from the manhole at this junction (inset photograph). A – upstream combined sewer (possibly containing mains leakage flow). B – downstream combined sewer (after inflow of captured water). C – watercourse inflow (captured water, but possibly receiving sewer misconnections).

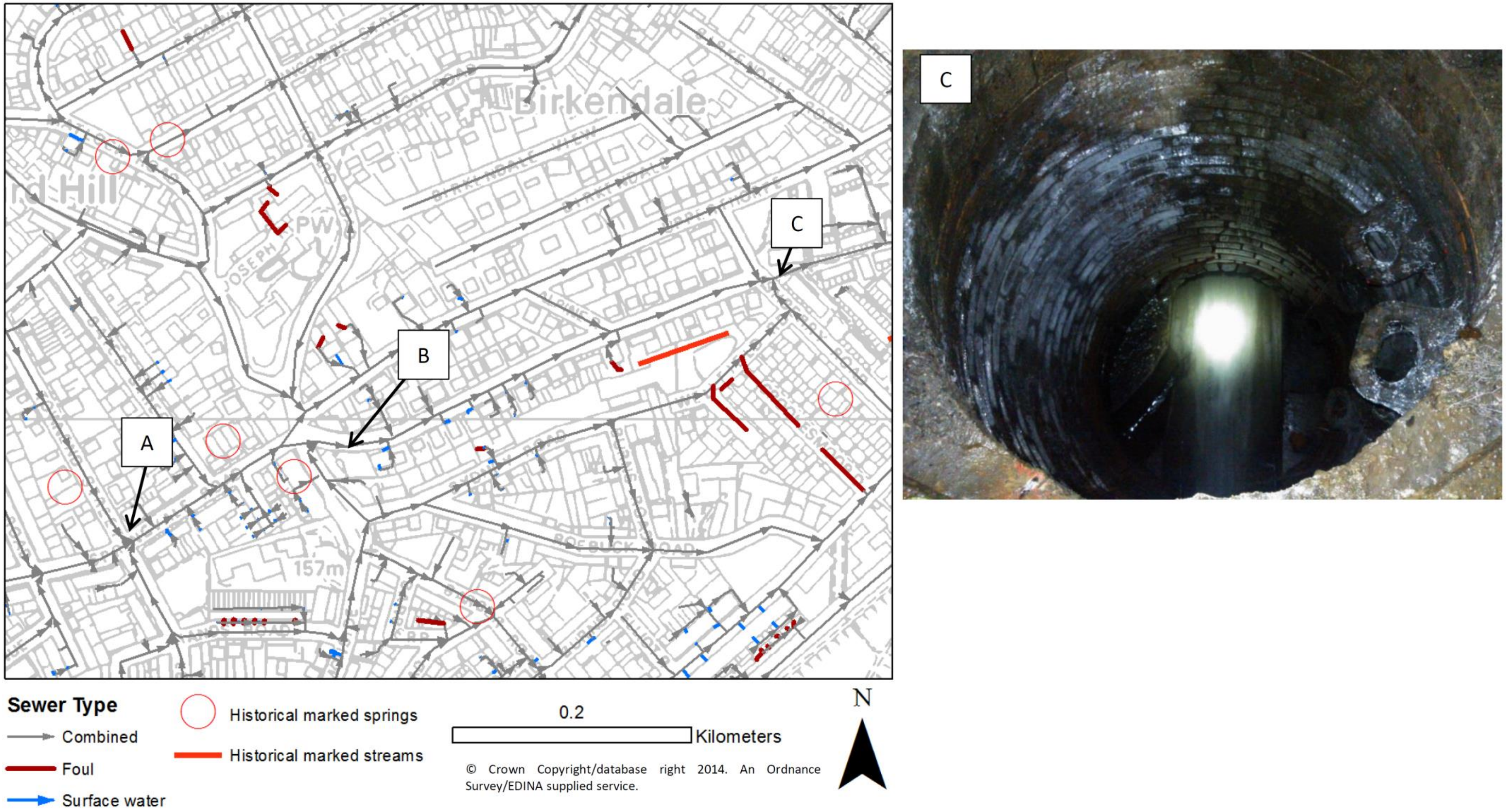


Figure 19 Sewer capture sample location map and pictures for site SR. Evidence shows numerous lost springs in this area, with Springvale Road running along a valley centreline. Historic maps show a lost watercourse further downstream. A – upstream sewer, lamphole (expected above most spring capture). B – middle sewer – lamphole (expected after most spring capture). C – downstream sewer (expected location of former watercourse converted to a sewer, inset photograph).

Figure 20 Sewer capture sample location map and pictures for site HB. A lost watercourse rises from historic springs flows in sewer designated for surface water but which is actually a sewerised watercourse. It becomes a combined sewer, but appears not to receive wastewater inputs immediately. A – watercourse sewer upstream of capture (inset photograph). B – downstream sewer after capture.

Figure 21 Sewer capture sample location map and pictures for site CV. A reservoir lies in a valley that once contained an historic watercourse, route shown from old maps, which has been converted into a combined sewer. A watercourse or spring inflow still flows into the reservoir. The reservoir outfall (inset photograph) flows to the combined sewer. A – upstream sewer, before capture. B – reservoir outfall, before capture. C – downstream sewer, after capture. X – open reservoir water.

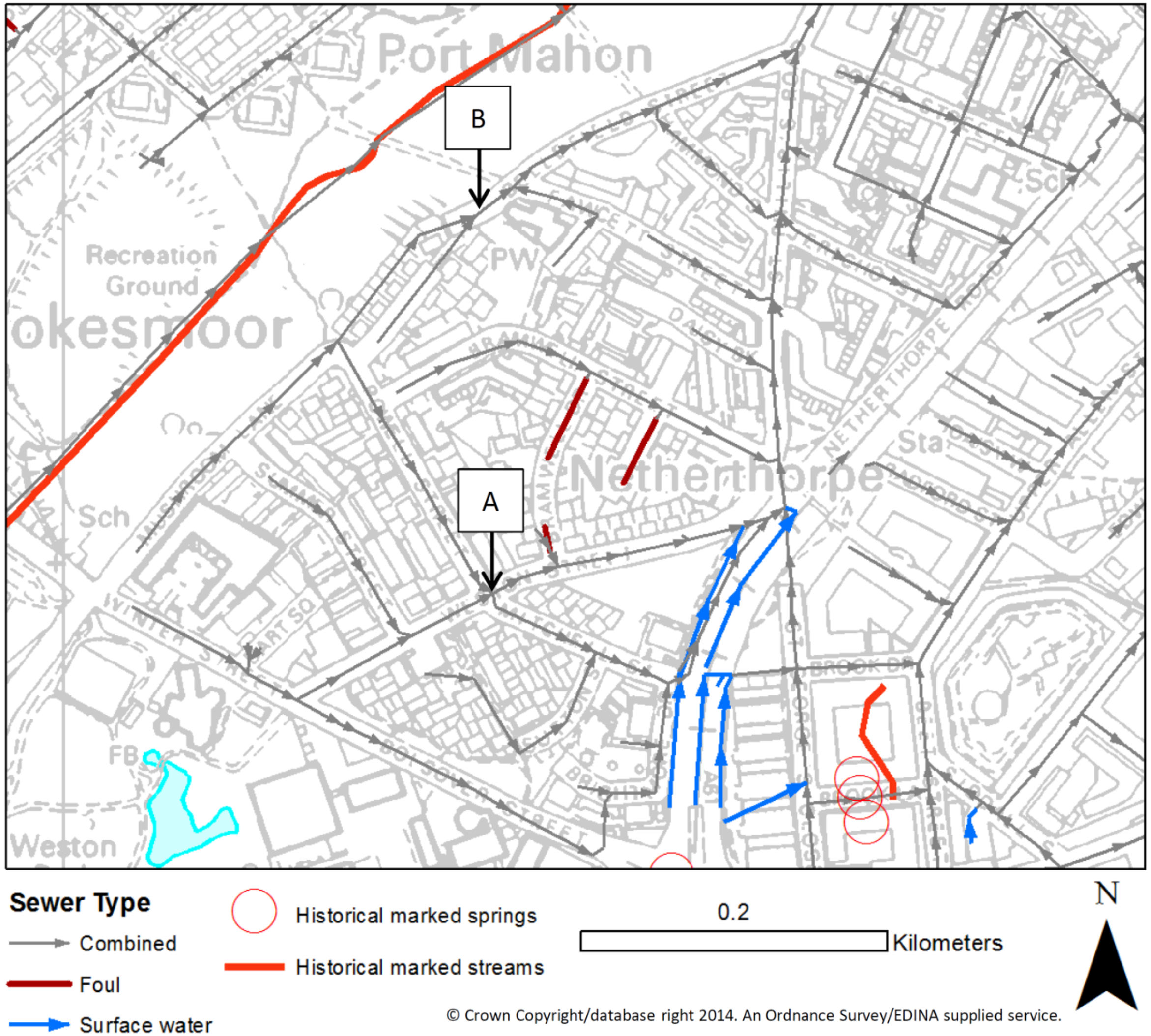


Figure 22 Sewer capture sample location map and pictures for site BS. Despite some possible lost streams in the area, there is no evidence of capture. A – main combined sewer, larger wastewater catchment displaying elevated night-time minimum flow according to flow data. B – side combined sewer, smaller receiving catchment.

Table 9 Summary details of sewer capture sites and expected water types.

Site	PW	SR	HB	CV	BS
Capture type	Capture by interception: *Open stream, culverted into surface water sewer, discrete inflow to combined sewer.*	Capture by conversion: *Downstream sewer along route of lost stream.* Direct spring capture: *Multiple lost springs, some flowing, drained to sewer.*	Capture by interception: *Culverted stream in surface water sewer, discrete inflow to combined sewer.*	Capture by conversion and interception: *downstream sewer along route of lost stream, reservoir outfall now connects to sewer.*	None expected. Infiltration-inflow possible in main sewer (A) due to elevated night-time minimum flow.
Night-time minimum flow (as % of daily average flow)	No data.	44% – between points A and B. 50% – between points B and C.	No data.	20% – at point A. 57% – at point C.	50% – downstream of point A. 13% – downstream of point B.
Other local conditions	Residential. Legacy contamination from ex-landfill.	Residential. No major industrial legacy.	Residential. Light industry. Probable industrial legacy contamination.	Residential. Possible legacy contamination.	Residential. Light industry and university labs.
Geology	Coal Measures.	Coal Measures.	Coal Measures.	Coal Measures.	Coal Measures.
Local springwater	Assumed from other Coal Measures springs. Typed directly at point X.	Assumed from springwater sample 12C.	Assumed from other Coal Measures springs. Typed directly at point X.	Assumed from other Coal Measures springs. Typed directly at point X.	Assumed from springwater sample 13.
Local tapwater	Wincoside and Manor WSZ.	Norton WSZ.	Loxley WSZ.	Manor WSZ, predominantly.	Manor WSZ.

Sampling methodology

In lieu of continuous sampling (installation of auto-samplers was not possible), multiple spot samples were taken to compare water types during two time periods:

- daily peak – either approximately 7 a.m. to 8 a.m. or 9 p.m. to 10 p.m. (as traffic conditions allow for access) when the input of wastewater reaches a maximum and thus where infiltration-inflow and captured flows will be proportionally at their minimum.
- night-time minimum – approximately 4 a.m. to 5 a.m. when the input of wastewater reaches a minimum and thus where infiltration-inflow and captured flows will be proportionally at their highest;

Multiple spot samples (typically between four and six) for each sample point at each site were taken within a 15-30 minute window during the two periods above, repeated over multiple consecutive days. This characterised the short and longer term chemistry variability. Three separate sampling weeks were arranged with the contractors in advance, with site PW sampled during 15^{th} to 19^{th} October 2013 (five days), sites SR and HB during 28^{th} October to 2^{nd} November (five days), and sites CV and BS during 11^{th} to 13^{th} November (three days).

Sewer capture samples were taken through manholes or lampholes using a plastic container on a rope. This was rinsed three times in the flow before decanting the sample into 500 ml polyethylene bottles, which were chilled and returned to the laboratory for processing within four hours. Samples were analysed for pH within six hours of collection, vacuum filtered through 0.45 µm filters, decanted into smaller bottles and refrigerated for later analysis. A 10 ml aliquot of filtered sample was preserved in 0.1 ml (1%) nitric acid for metals analysis.

It was not possible to specifically arrange the sampling programme around dry weather, and light drizzle was recorded throughout the sampling programme (**Figure 23**). Dry weather flow conditions (seven consecutive days without rainfall following seven consecutive days of rainfall <0.25 mm per day (Butler and Davies 2011)) were therefore not satisfied. While the influence of light drizzle and an isolated storm between the first two sampling weeks may have influenced the presence of infiltration-inflow from soilwater drainage, sewer flows were not visibly elevated as judged against the tide marks on the sewer walls, and so the impact of the weather is unlikely to have had significant bearing on the results.

Installing in-sewer flow meters was not possible due to access constraints. However, 12 months of continuous flow data were available for some sewer sites from a previous sampling programme in 2011, which informed the choice of time periods to obtain the night-time minimum and a daily peak.

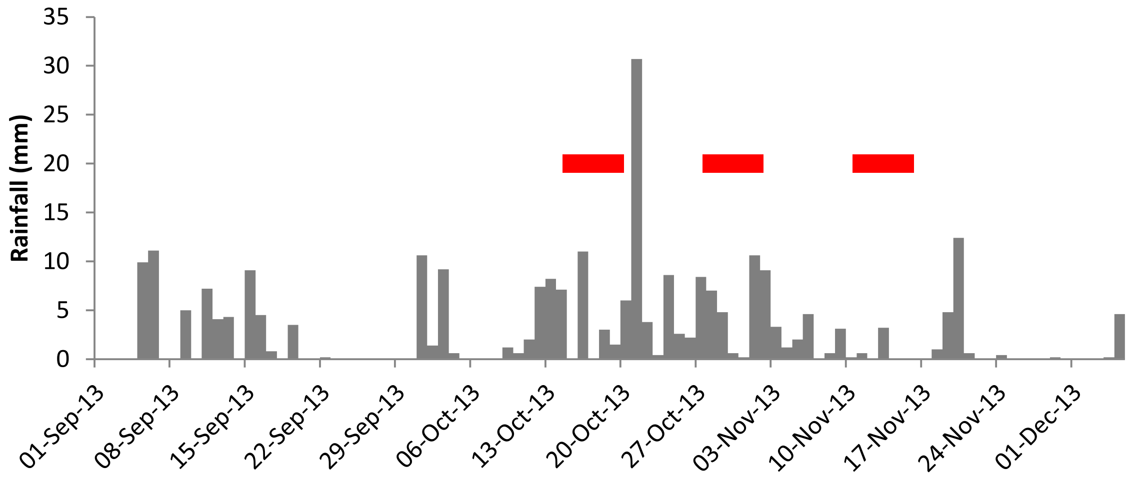


Figure 23 Daily rainfall data from Weston Park Weather Station (courtesy of Museums Sheffield), with the sampling weeks marked in red.

4.2.4 Analytical procedures

Analyses for all samples were conducted as follows:

- Alkalinity – measured on 40 ml of filtered sample using a Hach Digital Titration kit, used to calculate concentration of the HCO_3^- and CO_3^{2-} ions.
- Major ions and minor ions – measured on 1 ml filtered sample by Dionex Ion Chromatography, reporting 12 individual major and minor ions.
- Metals – measured on the 10 ml acid-preserved aliquot by ICP-MS, reporting 26 individual elements.
- Chemical Oxygen Demand (COD) – measured on 2 ml of filtered sample by Hach COD reagents, digested for 2 hours in a Hach reactor, and analysed using a portable Hach spectrophotometer (only conducted for the sewer capture sampling programme).

COD provides a benchmark against which to compare the water typing against conventional marker or pollutograph approaches.

For the sewer capture sampling programme, major ion measurements are of good quality, with generally satisfactory Charge Balance Errors (CBE) (mean 3.66; σ=5.27), with 93% of samples within a CBE of ±10% and 70% of samples within ±5%. 5% had very high CBE between ±15-26% caused by isolated errors in alkalinity measurement, and were discounted from the analysis. In general, the precision of alkalinity determination is weaker than the other tests, but repeat measurements found that the typical range of reported alkalinity concentrations did not significantly impact the calculated concentrations of HCO_3^- and CO_3^{2-}. Importantly, nor did it significantly affect the relative proportions of anions plotted in the Piper Diagrams, except in those cases of significant error described above.

CBE of the springwater samples reflect some isolated errors in the analysis. This is most likely accounted for by inaccurate alkalinity determination as the cation and anion determinations are otherwise consistent with expectations and the other samples. Five of these with unacceptable CBEs of ±15-52% were discounted from the analysis. The remaining samples have a satisfactory CBE (mean -1.10; σ=6.34). For the tapwater samples, CBEs were generally satisfactory (mean -1.92; σ=4.04).

4.2.5 Water typing analysis

For major ion water typing, Piper Diagrams are used to plot the percentage proportions of concentrations in milliequivalents per litre (meq/L) of major cation (Ca^{2+}; Mg^{2+}; Na^+ + K^+) and anion (SO_4^{2-}; HCO_3^- + CO_3^{2-}; Cl^-) species on two trilinear plots. Combinations of these are projected onto a diamond plot above (Piper 1944). In comparison with other techniques, such as Stiff Diagrams or Schoeller Plots, this permits easy visual differentiation of clusters of water types with regard to either the cations or anions, or a combination of the two (Freeze and Cherry 1979, Zaporozec 1972). Conservative mixing between two samples (i.e. a sewer containing both wastewater and captured water) will appear along a mixing line between two “end-points” (i.e. wastewater and captured water) on the Piper Diagram.

Minor ions and trace metals are interpreted with boxplots showing medians, quartiles and ranges of data. For each site, boxplots permit visual comparison between the concentrations found at each sample point and between day and night samples.

4.3 Results and analysis

The key results are summarised for each sample site in **Table 10**, detailing the predicted and observed major ion water types from the local tapwater and springwater typing studies, as well as summarising the minor ion and trace metals and COD results.

Table 10 Summary of results for each of the sewer capture sampling sites, detailing the predicted and observed outcomes of the major ion water typing by hypothesis, and the results of the other analyses.

Site	**PW**	**SR**	**HB**	**CV**	**BS**
Major ion hypotheses					
Clusters into major ion water types visible amid sample variability?	Yes.	Yes.	Yes.	Yes.	Yes (but less clear due to high variability).
Wastewater is similar to tapwater type (especially during day)?	Partially (cations only).	Partially (cations only).	No.	No.	Partially (cations only).
Watercourse is similar to springwater types of similar geology?	No.	No.	No.	No.	No (cations similar at night to spring/pond, but anions opposite).
Wastewater type varies diurnally in sewers trending to tighter cluster at night?	Yes.	Yes.	Yes.	Yes.	Yes.
Watercourse type consistent day and night?	No (due to probable wastewater misconnections).	N/A.	Yes.	Yes.	N/A.
Major ion water typing mixing interpretation?	Distinctive mixing between end-points. End-points not as expected (mains burst in sewer, and wastewater in watercourse). Cannot rule out presence of infiltration-inflow in sewer.	Upstream sewer water type similar day and night, and differentiated from mid and down-stream sewers, which trend slightly towards upstream sewer type at night. Cannot rule out presence of infiltration-inflow in sewer.	Water types only subtly differentiated with sewer trending towards a wastewater end-point during the day, and essentially same at night. Cannot rule out presence of infiltration-inflow in sewer.	Distinctive water types between upstream sewer and reservoir, with clear mixing in downstream sewer seen day and night. Cannot rule out presence of infiltration-inflow in sewer.	Distinctive night-time water types, both trending towards a wastewater end-point during the day. Cannot rule out presence of infiltration-inflow in sewer.
Major ion water typing successful?	Yes.	Partially.	Partially.	Yes.	Partially.
Other analyses					
Minor ions and trace metals corroborate major ion water typing?	Inflow enriched in minor ions compared to sewer, suggesting mains burst in upstream sewer and wastewater inputs in captured water after stream enters surface water sewer.	Enriched downstream day and night with some ions, diluted during day for others, possibly indicating geologic sources. Inconclusive.	Sewer enriched by day with some ions, enriched by watercourse with other possibly geologic ions. Similar to SR. Supports mixing and capture.	Captured water enriched in possibly geologic ions, so downstream shows some ions increase during day, others increase during night. Supports capture and mixing.	Uncertain. Main sewer enriched compared to offline sewer. Some ions appear anthropogenic sourced, but unclear overall interpretation.
COD results corroborate major ion water typing?	Supports observed inflow contamination by misconnections, and suggests mains burst in upstream sewer.	Supports wastewater enrichment during day, and trending towards less variable night-time water type.	Supports observed watercourse inflow having no misconnections, and suggests sewer near totally cleanwater at night.	Supports clean reservoir inflow to sewer. Variable wastewater COD but blending downstream.	Supports wastewater enrichment during day, trending towards less variable night-time water type.
Overall evidence for capture					
Capture?	Yes. Visually confirmed.	Uncertain. Effect of spring capture not seen in downstream samples. Upstream sample most likely contains spring water too.	Yes. Visually confirmed. Predominantly captured water at night.	Yes. Visually confirmed. Predominantly captured water at night.	No. No visual suggestion of capture.

4.3.1 Major ion water typing

Springwater characterisation

The water types of Sheffield's springwaters are varied with no distinctive type, as shown in **Figure 24**. While samples from within the same spring sites are relatively closely clustered with each other, there is no distinctive clustering of Coal Measures and Millstone Grit sites. This suggests that the underlying geology is not the only influence on the water types. The shallow groundwater chemistry will undoubtedly change as it reaches the surface and comes into contact with oxygen, or natural or anthropogenic contaminants.

Shallow groundwaters from both Millstone Grit and Coal Measures have previously been typed as being mainly Ca/Mg–SO_4^{2-} or Ca/Mg–HCO_3^- types, with some instances where nitrate is the dominant anion related to agricultural contamination (Banks 1997). These springwaters are of a broad range of water types, but are generally low in Mg^{2+} and HCO_3^- and CO_3^{2-}.

Tapwater characterisation

Sheffield tapwater major ion chemistry is split into two water types based on the WSZ: a calcium-dominated group and a sodium-dominated group (**Figure 25**). Samples from Loxley, Wincoside, Moonshine Ewden and external Severn Trent WSZs have proportionally higher Ca^{2+} concentrations and lower Mg^{2+}, Na^+ and K^+ concentrations than samples from Fullwood, Manor and Norton WSZs. The samples are more difficult to differentiate based on the anions than cations, where the clusters are closer and Moonshine Ewden WSZ appears across both clusters.

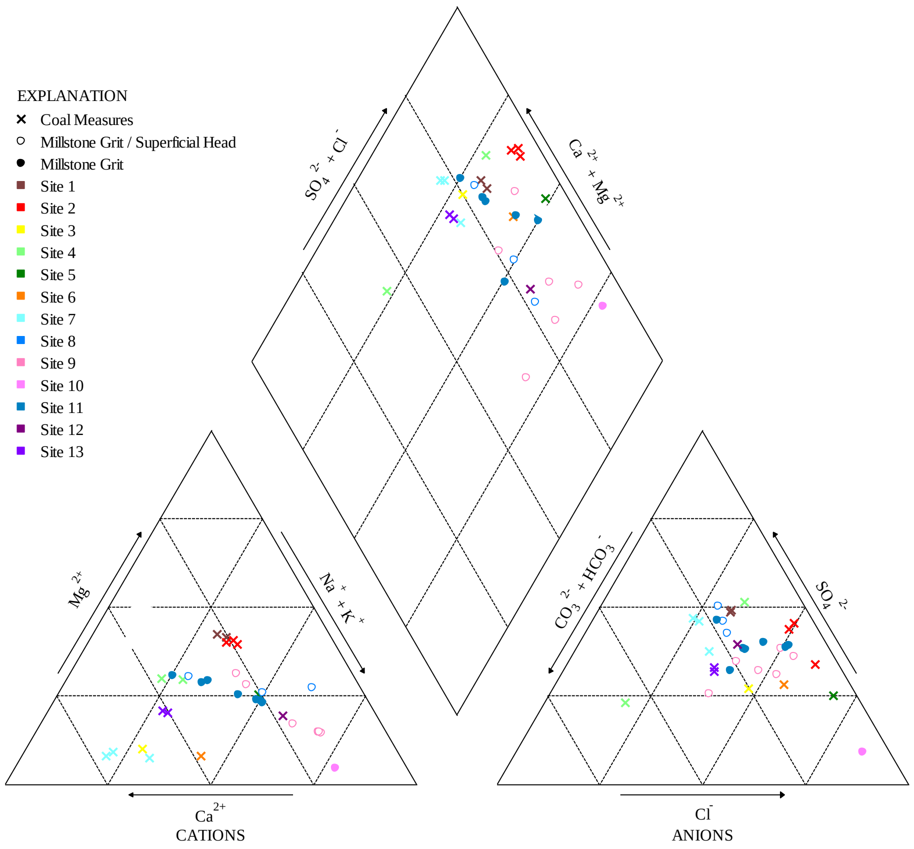


Figure 24 Piper Diagram of the springwater characterisation, showing no clearly discernible water type groups based on underlying geology. Even samples at the same site can be highly variable in water type.

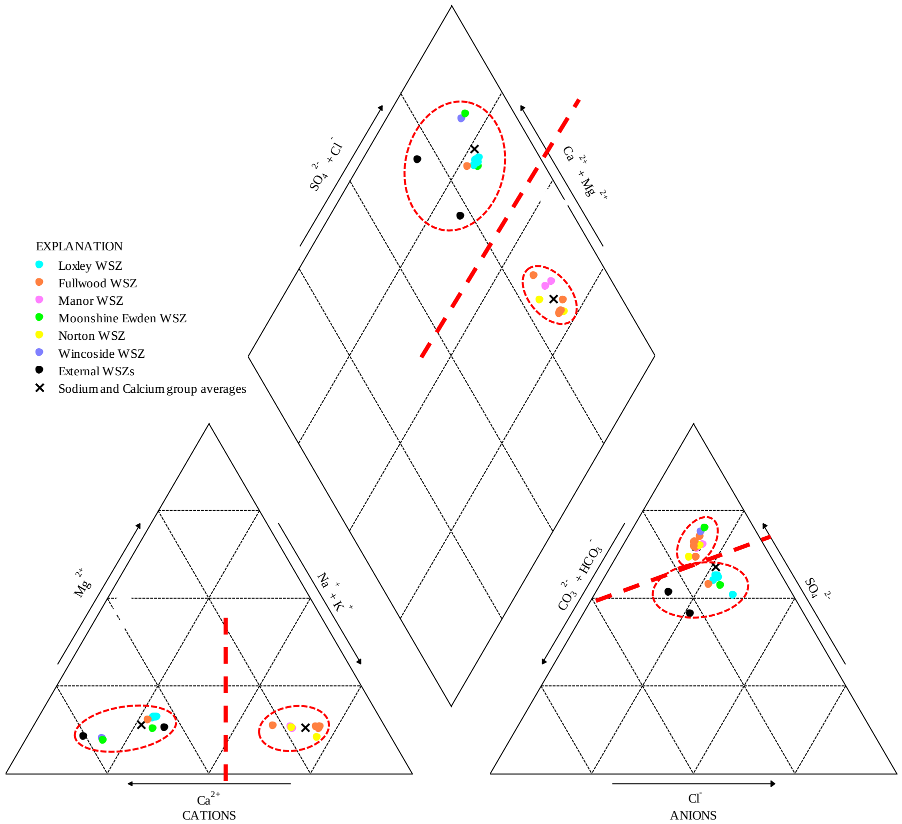


Figure 25 Piper Diagram of the tapwater characterisation, showing two clusters of tapwater types based on Water Supply Zone (WSZ).

Sewer capture

The major ion water typing results plotted in Piper Diagrams (**Figures 26-30**) show that each site has a unique pattern to be interpreted. Samples are generally of mixed water type, i.e. not dominated by particular ions, though typically characterised by lower Mg^{2+} concentration proportions than the other cations. At all sites there is an observable clustering by sample point, which is sometimes clear only with either cations or anions. Differentiation is mostly with regard to the Na^{+}+K^{+} cation axis and Cl^{-} or SO_4^{2-} anion axes.

The results for site CV are described first, because they clearly demonstrate the detection of captured water. The commonalities and discrepancies in the results from other sites are then discussed.

Demonstration of results at site CV

The watercourse (reservoir, point X) at CV displays a clearly clustered water type end-point at its outfall to the sewer system (point B) (**Figure 26**). As expected, this is consistent day and night, reflecting a lack of wastewater input influence. The upstream sewer (A) is a distinctly different water type to the watercourse end-point, characterised by higher Na^{+}+K^{+} proportions. This is relatively closely clustered at night, increasing in variability during the daytime towards a wastewater end-point characterised by elevated Na^{+}+K^{+} proportions. Differentiation is clearest with cations rather than anions.

The watercourse end-points do not correspond closely with local springwater types on similar Coal Measures geology, and the wastewater end-points do not correspond closely with the local tapwater types. The watercourse and wastewater end-points could therefore not have been confidently predicted for this site, demonstrating the importance of being able to sample end-points individually and together downstream after mixing.

The downstream sewer samples lie along a distinctive mixing line between the watercourse and wastewater end-points. Again, the clustering is tighter at the night-time minimum, but clearly trends towards the watercourse end-point at night and the wastewater chemistry during the day. This case confidently demonstrates the effectiveness of the major ion water typing.

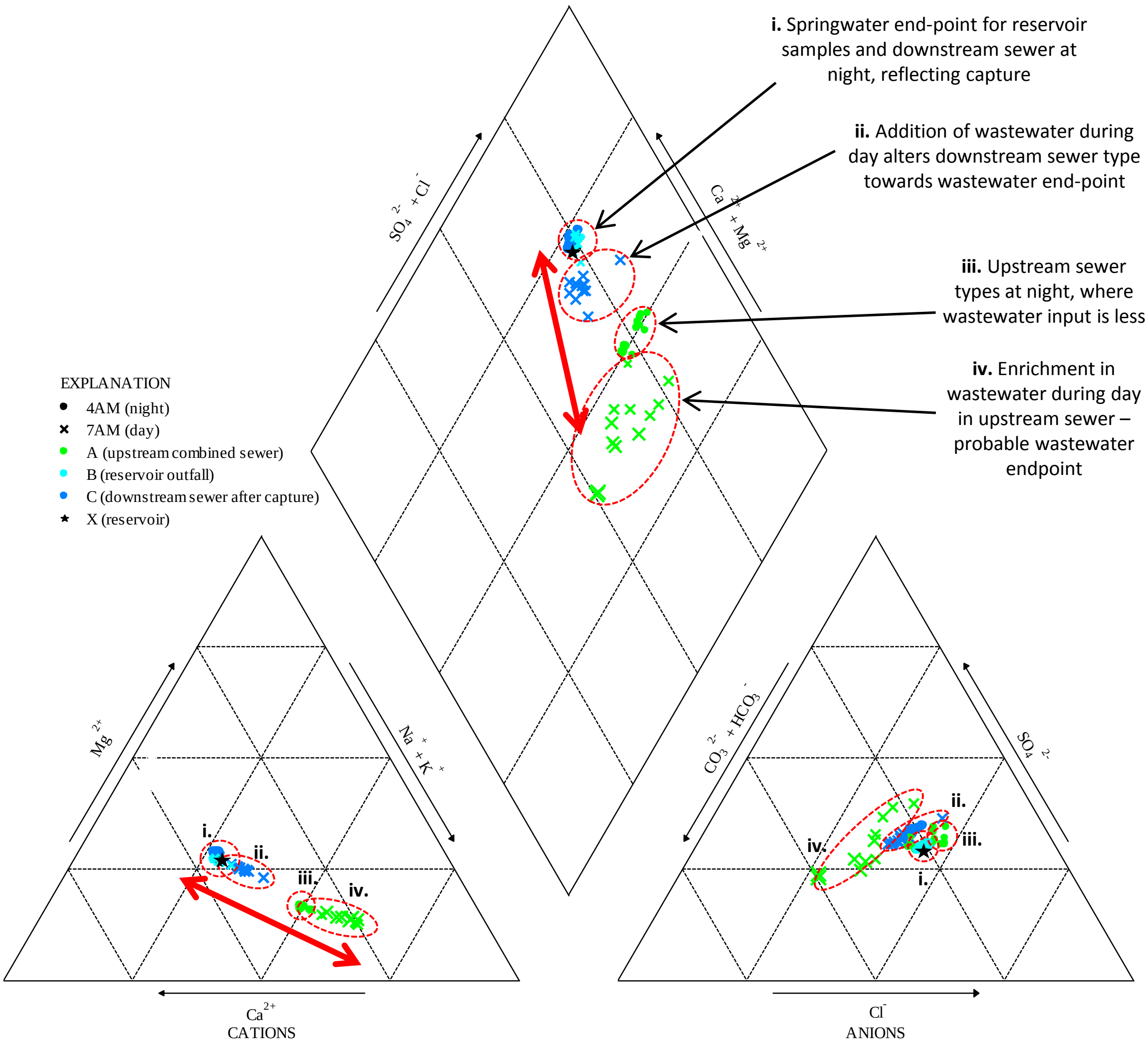


Figure 26 Piper Diagram for site CV showing distinctive clustering of water types. The upstream sewer sample points are a different water type to the samples from the reservoir outfall. The water types of the downstream sewer lie on a mixing line between the two end-points, trending towards the wastewater end-point during the daytime samples, and being essentially the same as the captured water end-point during the night-time.

Sewer capture at other sites

Similar results and patterns are observed at other sites, but the commonalities and discrepancies are now discussed to draw out the important lessons from the study.

In no cases do the watercourse or wastewater end-points clearly match the water types predicted from local spring samples or tapwaters, reflecting the importance of being able to type these end-points at each site. A distinctive mixing line is visible at PW between the open watercourse samples (X) and the upstream sewer samples (A) (**Figure 27**). The watercourse inflow just prior to capture (C) is close to the upstream watercourse end-point, but perhaps reflecting the observed sewage misconnection inputs somewhere along this reach, is shifted towards the sewer end-point slightly. The upstream sewer, however, does not precisely reflect a wastewater end-point; CCTV after sampling confirmed that it receives a considerable flow from a burst mains pipe. However, the mains burst water at night did not correspond exactly with the local tapwater type for both cations and anions, but the daytime samples where wastewater flushes were observed in the sewer are mostly clustered around this water type and trending towards elevated Na^{+}+K^{+} proportions. Despite this, a clear mixing line is seen as at site CV, with the downstream sewer samples (B) demonstrating mixing between the two end-points, and trending towards the watercourse end-point by night, and the wastewater/mains burst end-point at day.

The results also demonstrate the need for sufficient sampling locations. Major ion water typing relies on comparative assessment, and cannot reliably detect capture from a single sample point. At site HB, there is distinctive clustering but very similar water types between the watercourse end-point and wastewater end-point (**Figure 29**). During the day, the downstream sewer (B) water type trends away from the watercourse (A) type towards elevated Na^{+}+K^{+} proportions. Because it was not possible to access the sewer to sample upstream of the capture, it is not possible to confirm the true wastewater end-point. The question remains: is the downstream sewer dominated by the captured water end-point, or does it just happen to be only subtly different, or does the upstream sewer also contain substantial amounts of infiltration-inflow or unanticipated capture of the local watercourse type?

Site SR demonstrates the limitation of the major ion water typing method when applied where capture is not via a discrete known inflow, but by multiple, unknown diffuse inflows of directly captured springs, or where a combined sewer has been converted into a watercourse (**Figure 28**). The upstream sewer (A) was anticipated to be above the spring-line, and reflect a distinctive wastewater end-point. The influence of captured flow was expected to be observed at the middle and downstream sewers (B and C) by water types trending towards the local springwater end-point at night, as predicted from typing an open spring in this vicinity (springwater sample 12C). At this site, the upstream sewer samples are similar day and night and, differentiated most clearly by anion proportions, are different water types to the middle and downstream sewers. The middle and downstream sewers were similar to each other, varying between distinctive night and daytime end-points, but these didn’t correspond with either the tapwater or local springwater types. Furthermore, the water typing is unclear, as the cations suggest that the night-time samples at B and C are similar to the upstream sewer samples, perhaps suggesting a common spring-fed end-point at both. However, this is not certain because the anion clusters suggest that A is distinctly different to B and C at all times.

At site BS, where no capture was expected, there is no clear indication of capture in the water types (**Figure 30**). The water type of the main sewer (A), with its larger contributing drainage area and possibility of encountering infiltration-inflow, might have been expected to be different from the side sewer (B) which sits away from any expected capture. Differentiation between the water type clusters in the two sewers is less clear than with the other sites, with greater variability especially during the day, and much less clear differentiation between night and day (though both sewers appear to follow the trend for elevated Na^{+}+K^{+} proportions during the day).

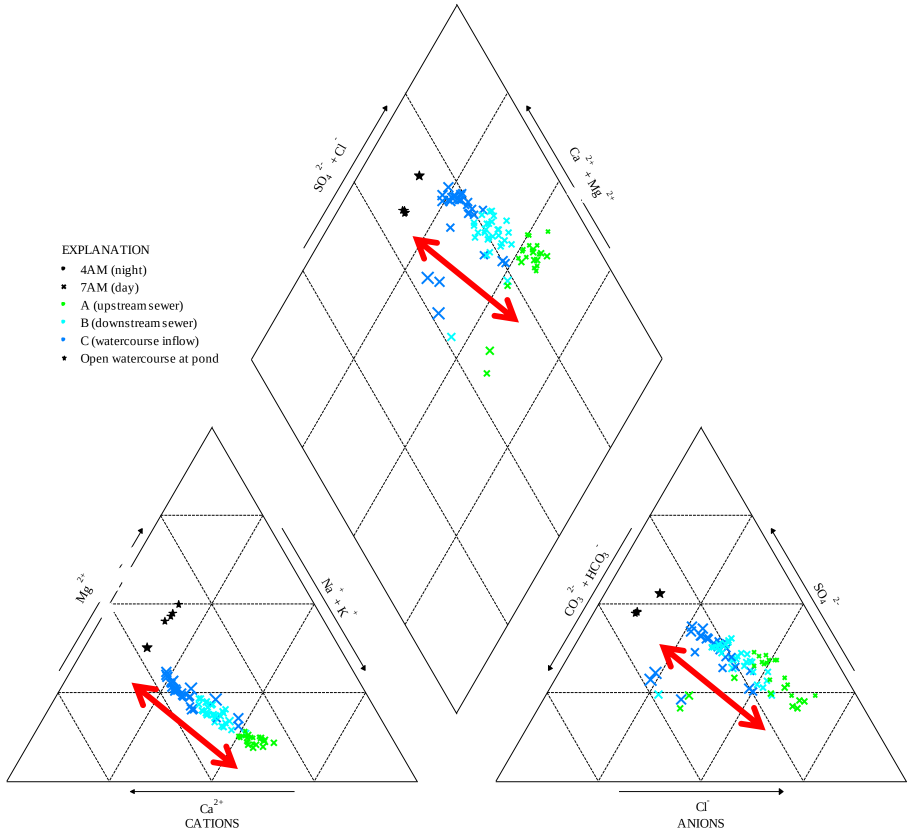


Figure 27 Piper Diagram for site PW showing distinctive clustering of water types. Samples lie on a mixing line between the open watercourse end-point and an end-point of the upstream sewer. The downstream sewer samples lie on this mixing line, trending towards the watercourse end-point at night.

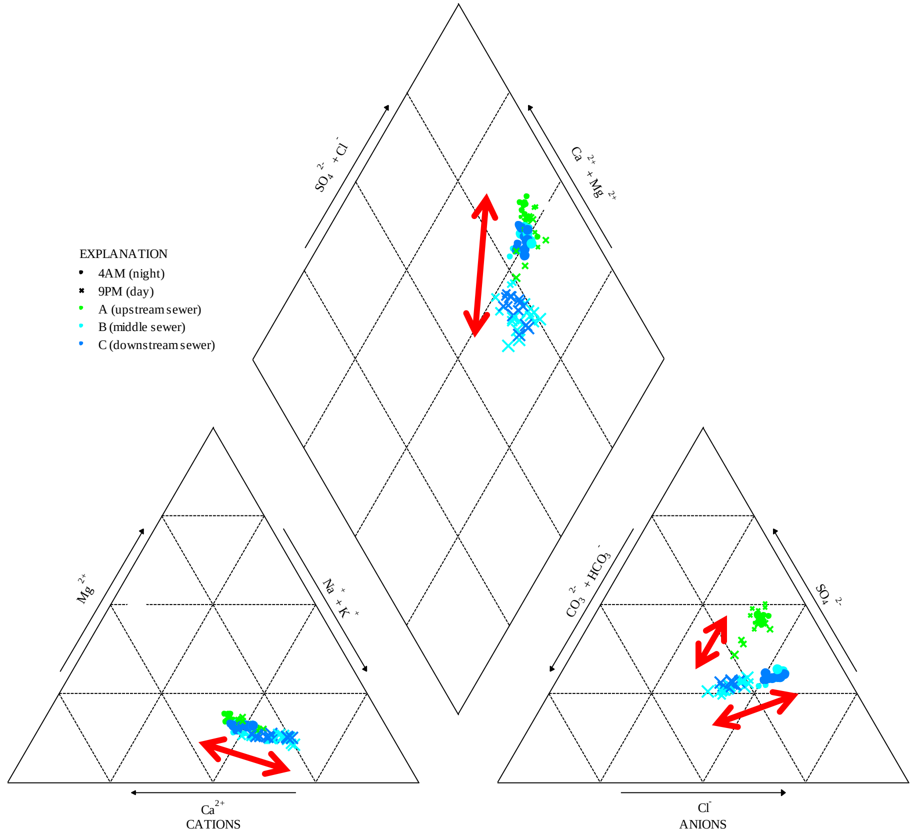


Figure 28 Piper Diagram for site SR showing distinctive clustering of water types, most clearly differentiated by anions, which show the upstream sewer to be of different water type to the middle and downstream sewers, though neither grouping appear to correspond with local springwaters.

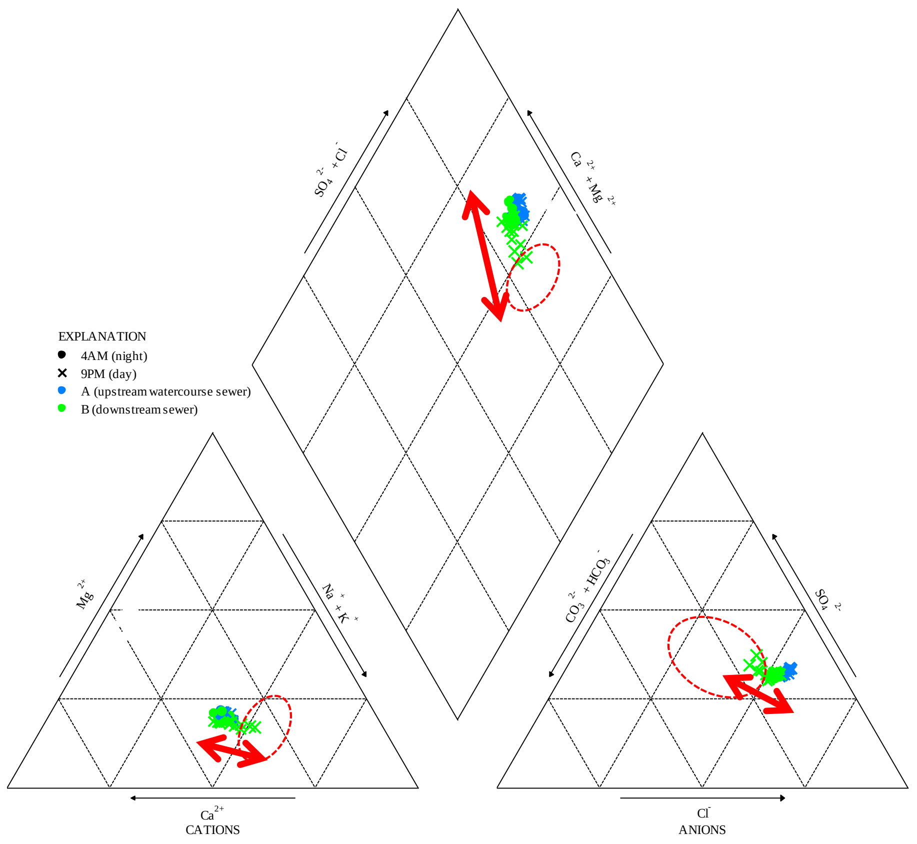


Figure 29 Piper Diagram for site HB showing distinctive but very similar clustering differentiating the captured water and the downstream sewer. Daytime sewer samples trend towards a hypothesised wastewater end-point, away from the captured water type.

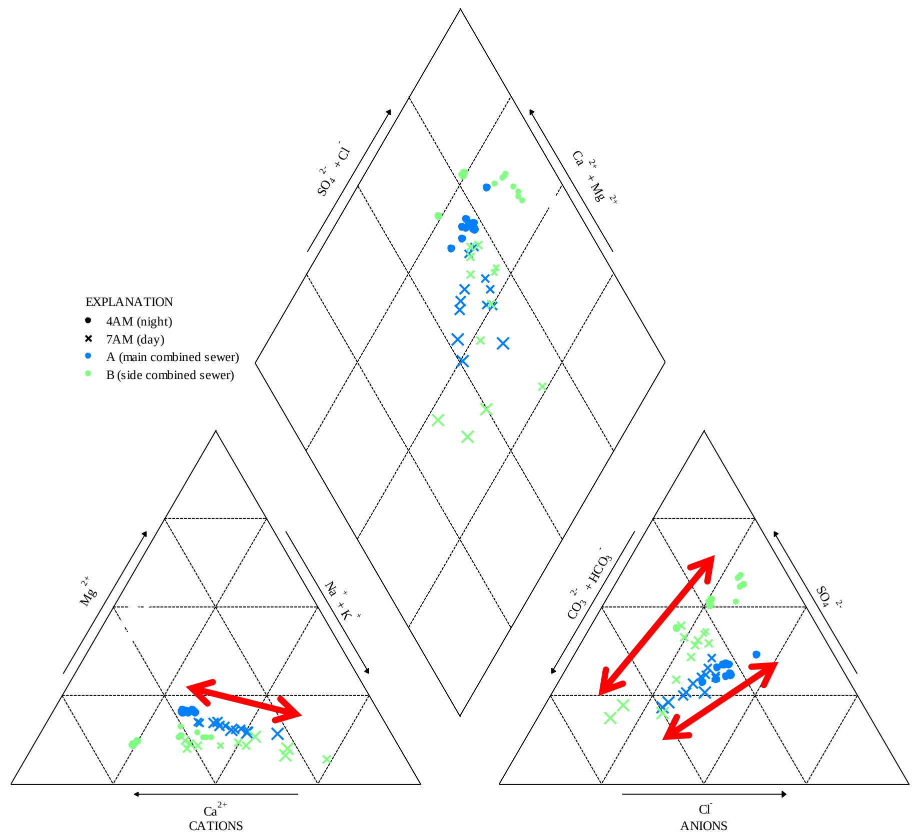


Figure 30 Piper Diagram for site BS, showing clustering between the two sample points and a spread from night-time to daytime water types. No discernible mixing line is clearly evident.

4.3.2 Quantification of captured flow in the combined sewer

For sites where there is a distinctive mixing between watercourse and wastewater end-points, the proportions of captured flow in the sewer have been approximated by quantifying the mixing. A sample from the centre of the cluster of upstream sewer samples during the daytime represents the wastewater end-point, and the directly sampled watercourse water represents the captured water end-point. Simple conservative mixing of the cation and anion concentrations was calculated between the two end-point solutions.

This is illustrated for site CV in **Figure 31**. Focusing on the cation concentrations, the downstream sewer samples consist of approximately 60-90% captured water during the daytime. At the night-time minimum, this value approaches 95-100% captured water. The precision with which capture can be quantified in this way is limited by how closely the samples are clustered on the Piper Diagram. As the daytime samples have greater variability in water type than at the night-time minimum, there is accordingly a wider estimate of the percentage proportion. The water type clusters are not clearly differentiated by anions, and so quantifying a mixing line is not possible.

At PW, the sewer downstream of capture (B) contains in the range of 40-85% watercourse flow at the night-time minimum (**Figure 32**). A more precise quantification is not possible due to the scatter in the clustering of the downstream samples along the mixing line caused by short-term variability in the downstream wastewater chemistry (B), and by the scatter in the clustering around the end-points. Identifying a single accurate end-point may not be possible due to the normal variation in sample chemistry. Furthermore, the watercourse inflow (C) does not correspond completely with the upstream watercourse (X) water types; the possible addition of contaminants (such as from sewer misconnections) makes it difficult to be confident of the true end-point. Also, the upstream sewer (A) probably represents an unknown mixing between the wastewater and leaking mains water.

Quantifying capture at the other sites is more difficult because the major ion water typing of springwaters, tapwaters and sewers indicated no reliable end-points for the captured flow or wastewater.

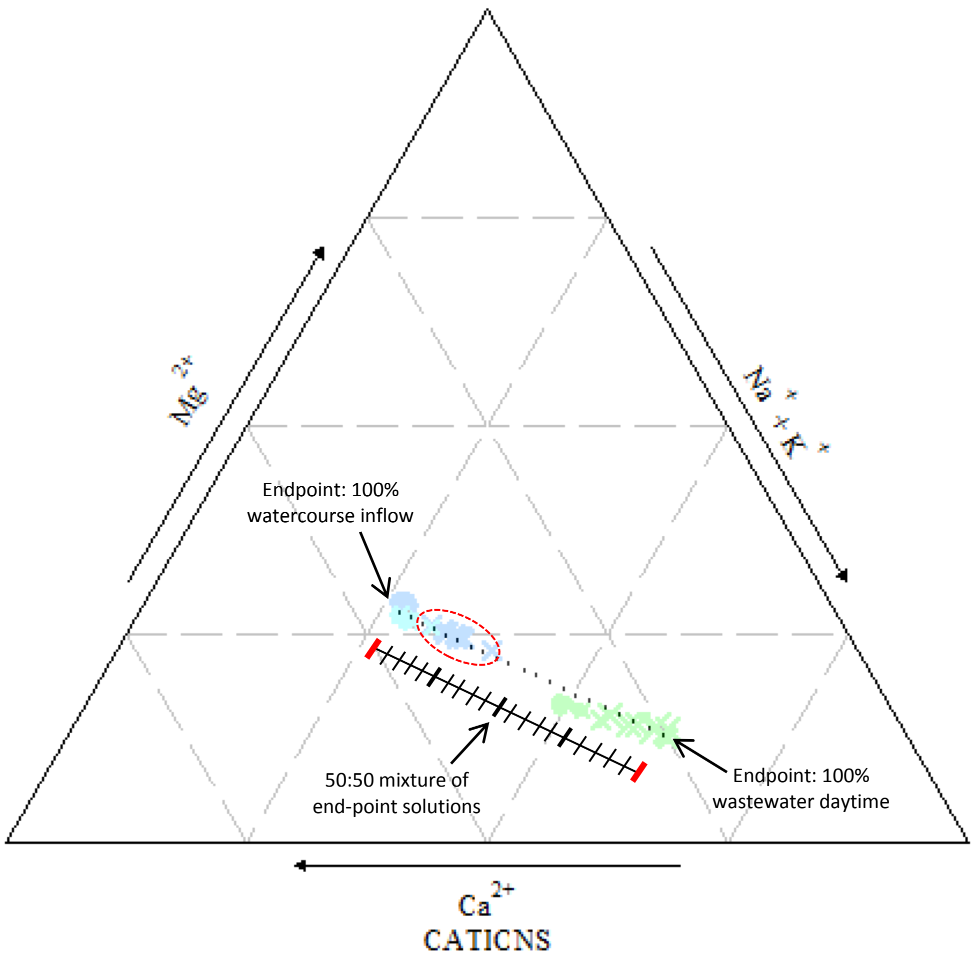


Figure 31 Quantification of proportions of captured flow in the downstream sewer (C) at site CV. Simple mixing of end-point solutions was calculated at different ratios to quantify the cation mixing line, plotted alongside, showing non-linearity of scale, in order to read off the range of proportions where the downstream sewer sample cluster lies (circled).

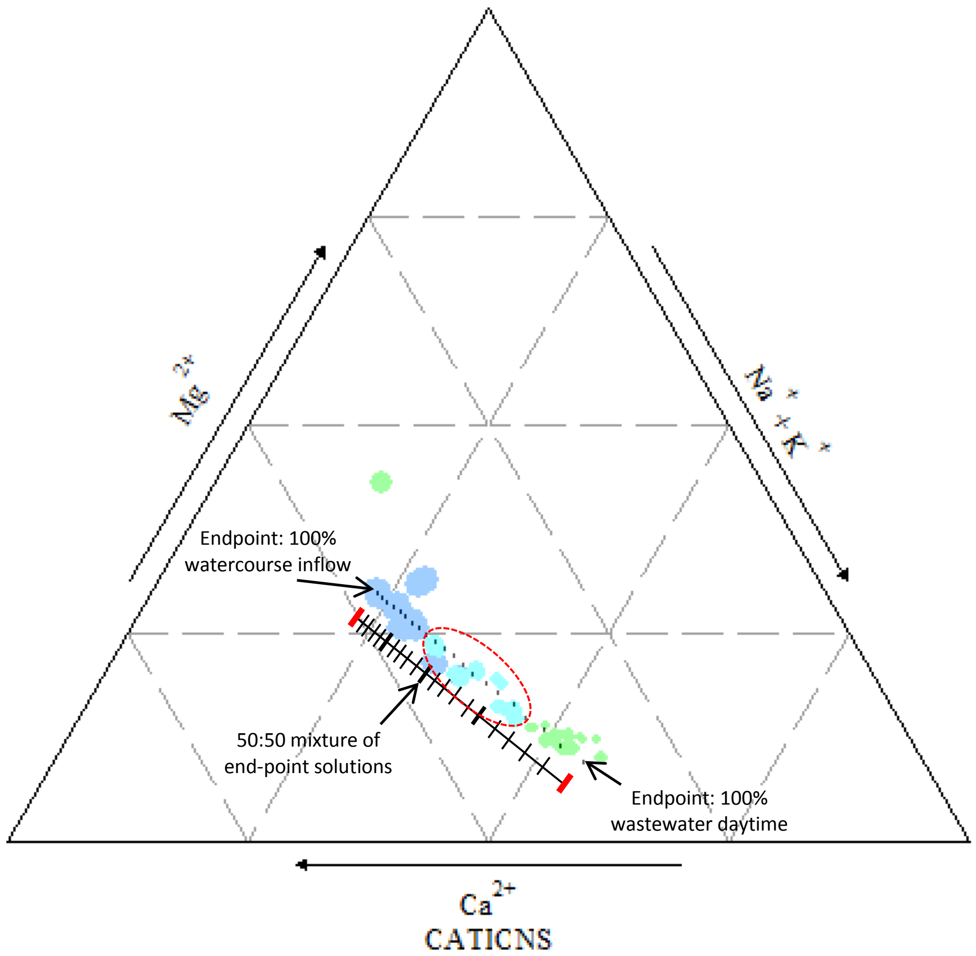


Figure 32 Quantification of proportions of captured flow in the downstream sewer (B) at site PW. Simple mixing of end-point solutions was calculated at different ratios to quantify the cation mixing line, plotted alongside, showing non-linearity of scale, in order to read off the range of proportions where the downstream sewer sample cluster lies (circled).

4.3.3 Minor ions and trace metals

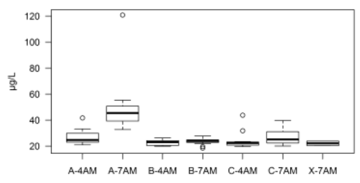
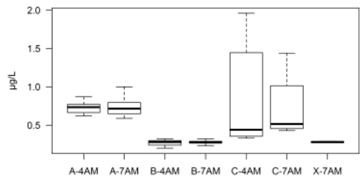
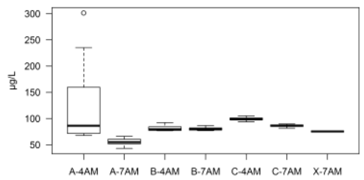
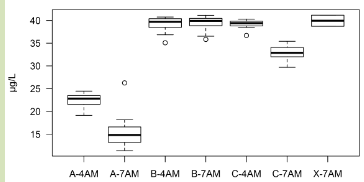
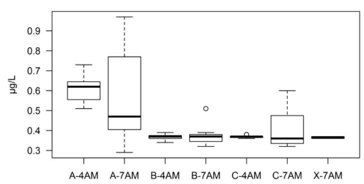
Sewer capture

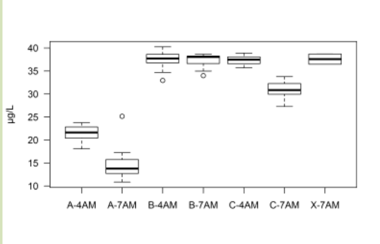
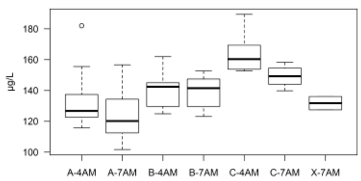
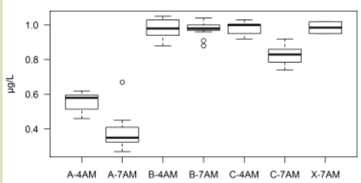
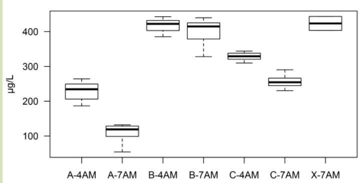
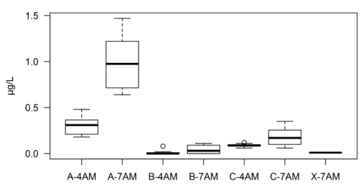
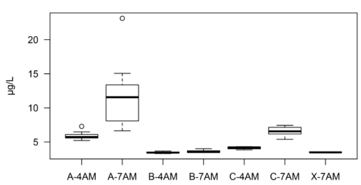
Minor ions and trace metals were interrogated for patterns using boxplots. All analysed elements have a variety of sources, including domestic wastewater, industrial effluents, legacy contamination, and natural geological sources (Drever 1982, Fetter 1993, Fetter 2001, Freeze and Cherry 1979, Manahan 2010). This makes none of them ideal markers.

However, there was a clear pattern between those metals (Ba, Cs, Ga, Sr, Te and U) that were consistently higher in watercourse samples and lower in wastewater samples, indicating a possible natural geological origin. They had strong positive correlations with each other. Studies suggest that the Coal Measures geology may contain some of these elements, however these have not been the focus of previous studies characterising these waters (Banks 1997), and they can also be associated with past and present industrial contamination. At all sites there is dilution of these elements where captured water mixes with wastewater, and where wastewater increases during the daytime compared to the night-time minimum. These could be potential markers of captured waters. The results are shown for site CV in **Table 11**, with results from all sites and springwater and tapwaters in Appendix D.

Conversely, Cu, Pb and Rb appear to be markers of wastewater, being higher during the day than the night, being lower in watercourse samples, and becoming diluted in sewers with captured water inflows. These are broadly explained as typical products of domestic wastewater activity, despite numerous possible natural sources. The other minor ions and metals show greater variability among samples, owing to their numerous natural and anthropogenic sources, and consequently do not greatly help to distinguish water types. PO_4^{3-}:NH_4^+ ratios were expected to reflect domestic foul sewage inputs, and PO_4^{3-}:B ratios were expected to reflect domestic laundry and detergent inputs, but no consistent patterns that helped to differentiate captured sources from wastewater were noted.

Table 11 Minor ion and trace metal boxplots and explanations for site CV. Green cells reflect elements shown in all sites to be elevated in natural waters and low in wastewaters, i.e. markers of capture. A=upstream sewer; B=reservoir outfall; C=downstream sewer; X=reservoir. See Appendix D for all results.

Boxplot key	**Explanation**
 Al	Baseline concentration lower in the reservoir waters (B and X) than the wastewater (A). Relatively strong grouping differentiates water types. Upstream sewer concentration significantly increases during the day indicating anthropogenic wastewater sources. Samples from B and X do not vary day and night, as expected, indicating a background concentration. The concentration in the downstream sewer with capture (C) is similar to the reservoir water at night, trending upwards towards wastewater during the day, reflecting mixing between the inputs.
 As	Reservoir waters (B, X) have essentially no As. Significantly higher concentrations in upstream sewer both day and night indicates not a typical domestic wastewater input, but a characteristic chemical of the sewers in this location or an activity that occurs both day and night. Downstream sewer (C) has elevated average concentrations both day and night between the two end-points, but with a substantially wider variation. This suggests a source with a degree of variability, or reflects a process – such as related to mobilisation of As – resulting in variable concentrations.
 B	Relatively abundent in all samples, with a baseline in the reservoir waters (B, X) similar to wastewaters (A). Relatively narrow range of values for all samples except those during night at upstream sewer, which include samples notably enriched in concentration. This could reflect isolated domestic activity using detergent during the night, which because sewer flows are low, results in strong effect on the concentration. Despite this, there is no clear difference in concentrations between reservoir waters and wastewaters.
 Ba	Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. **This is a marker of local captured waters.**
 Co	Baseline concentration lower in the reservoir waters (B and X) than the wastewater (A). Relatively strong grouping differentiates water types. Upstream sewer concentrations more variable during the day but lower on average, indicating possible varied and inconsistent anthropogenic wastewater inputs. Samples from B and X do not vary day and night, as expected, indicating a background concentration. The concentration in the downstream sewer with capture (C) is similar to the reservoir water at night, trending upwards towards wastewater in some samples (but not on average) during the day.

<table>
<tr><td>
Cs</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>
Fe</td><td>Relatively abundent in all samples, with a baseline in the reservoir waters (B, X) similar or slightly higher than wastewaters (A). The variability in concentrations is similar in each sample point, with some overlap. The lack of significant difference between concentration of wastewaters at day and night suggests that this is not generally an anthropogenic input in wastewater. The elevated levels in the downstream sewer (C) especially during the night may be explained by the short section of iron sewer pipe material recorded in the sewer map database downstream of points A and B and upstream of C.</td></tr>
<tr><td>
Ga</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>
Mn</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, closer in concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>
Pb</td><td>Almost entirely not present in the reservoir waters (B and X), with a significantly higher concentration in the wastewater (A). Relatively strong grouping differentiates water types. Upstream sewer concentration significantly increases during the day indicating anthropogenic wastewater sources. Samples from B and X do not vary much by day and night, as expected. The concentration in the downstream sewer with capture (C) is similar to the reservoir water at night, trending upwards slightly towards wastewater during the day, reflecting mixing between the inputs. This is a marker – by absence – of local captured waters.</td></tr>
<tr><td>
Rb</td><td>Almost entirely not present in the reservoir waters (B and X), with a significantly higher concentration in the wastewater (A). Relatively strong grouping differentiates water types. Upstream sewer concentration significantly increases during the day indicating anthropogenic wastewater sources. Samples from B and X do not vary much by day and night, as expected. The concentration in the downstream sewer with capture (C) is similar to the reservoir water at night, trending upwards slightly towards wastewater during the day, reflecting mixing between the inputs. This is a marker – by absence – of local captured waters.</td></tr>
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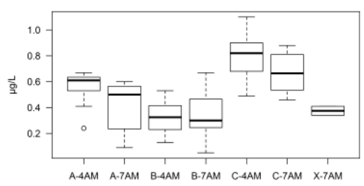
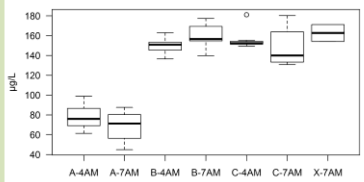
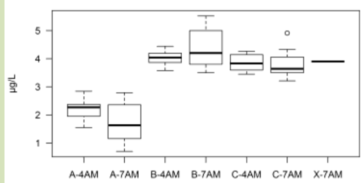
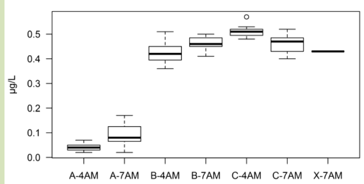
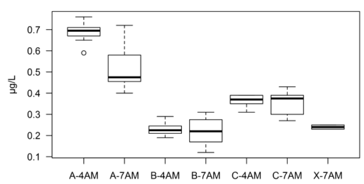
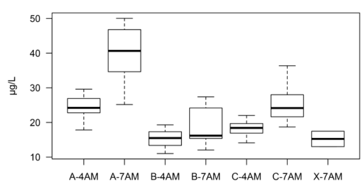
<tr><td>

Se</td><td>Baseline in the reservoir waters (B, X) similar or slightly lower than wastewaters (A), but overlap of sample concentrations makes differentiation difficult. The lack of significant difference between concentration of wastewaters at day and night suggests that this is not generally an anthropogenic input in wastewater. The elevated levels in the downstream sewer (C) especially during the night could be explained by other inputs to the system.</td></tr>
<tr><td>

Sr</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>

Te</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>

U</td><td>Significantly higher concentrations in reservoir waters (B, X) than in wastewater (A). The concentration in the upstream sewer (A) reduces during the day, indicating dilution of a background concentration in any present drainage water by wastewater inputs. The downstream sewer (C) reflects capture, with a similar concentration to reservoir waters during night, and diluted by the wastewaters towards the wastewater end-point during the day. This is a marker of local captured waters.</td></tr>
<tr><td>

V</td><td>Baseline concentration lower in the reservoir waters (B and X) than the wastewater (A). Relatively strong grouping differentiates water types. Upstream sewer concentrations more variable during the day but lower on average, indicating possible varied and inconsistent anthropogenic wastewater inputs. Samples from B and X do not vary significantly day and night, as expected, indicating a low background concentration. The concentration in the downstream sewer with capture (C) reflects mixing between the two end-point concentrations.</td></tr>
<tr><td>

Zn</td><td>Baseline concentration lower in the reservoir waters (B and X) than the wastewater (A). Relatively strong grouping differentiates water types, but an unusual increase in concentration in some reservoir samples (B) during the day, not readily supported by other analyses suggests an analytical error rather than wastewater inputs. Upstream sewer concentrations enriched during the day, indicating consistent anthropogenic wastewater input. The concentration in the downstream sewer with capture (C) reflects mixing between the two end-point concentrations.</td></tr>
</table>

Springwater and tapwater

The trace metals identified as being elevated in watercourse samples (Ba, Cs, Ga, Sr, Te and U) were consistently low in all tapwater samples (in both the calcium- and sodium-dominated groups) and generally at similar concentrations in the springwater samples (in both Millstone Grit and Coal Measures geologies). These corroborate the observed patterns.

4.3.4 COD

Concentrations ranged from 0 mg/L to >250 mg/L COD. COD was consistently higher in wastewater samples than watercourse samples, as expected (**Figure 33**). Also as expected, the watercourse samples are similar day and night (with the notable exception of point C at site PW, supporting observations of misconnected wastewater inputs prior to capture), and the wastewater samples were higher during the daytime than night-time minimum. COD also reflects the mixing between the watercourse and wastewater end-points, corroborating the major ion water typing interpretations.

Despite no flow monitoring being available for this sample programme, the COD results confirm that the sewer samples demonstrate the expected diurnal variation, and that given flow data, the pollutant-hydrograph method might be applied against which to benchmark the water typing. The watercourses, while relatively clean, were rarely consistently close to 0 mg/L COD. In the watercourse samples, COD concentrations ranged from 7 mg/L to 35 mg/L (mean 15 mg/L). The pollutant-hydrograph method widely used for detecting infiltration-inflow to sewers assumes 0 mg/L COD for inflowing groundwater. This assumption would make this method less reliable to apply for detecting captured streams and springs that, while not necessarily polluted by sewage, may reflect minor contamination from a variety of urban sources. The use of minor ions and trace metals that appear to consistently be abundant in captured waters whilst negligible in wastewater, or vice versa, may be more appropriate markers than COD to apply in a pollutant-hydrograph approach (excepting consideration of the comparative practicalities and costs of analysis).

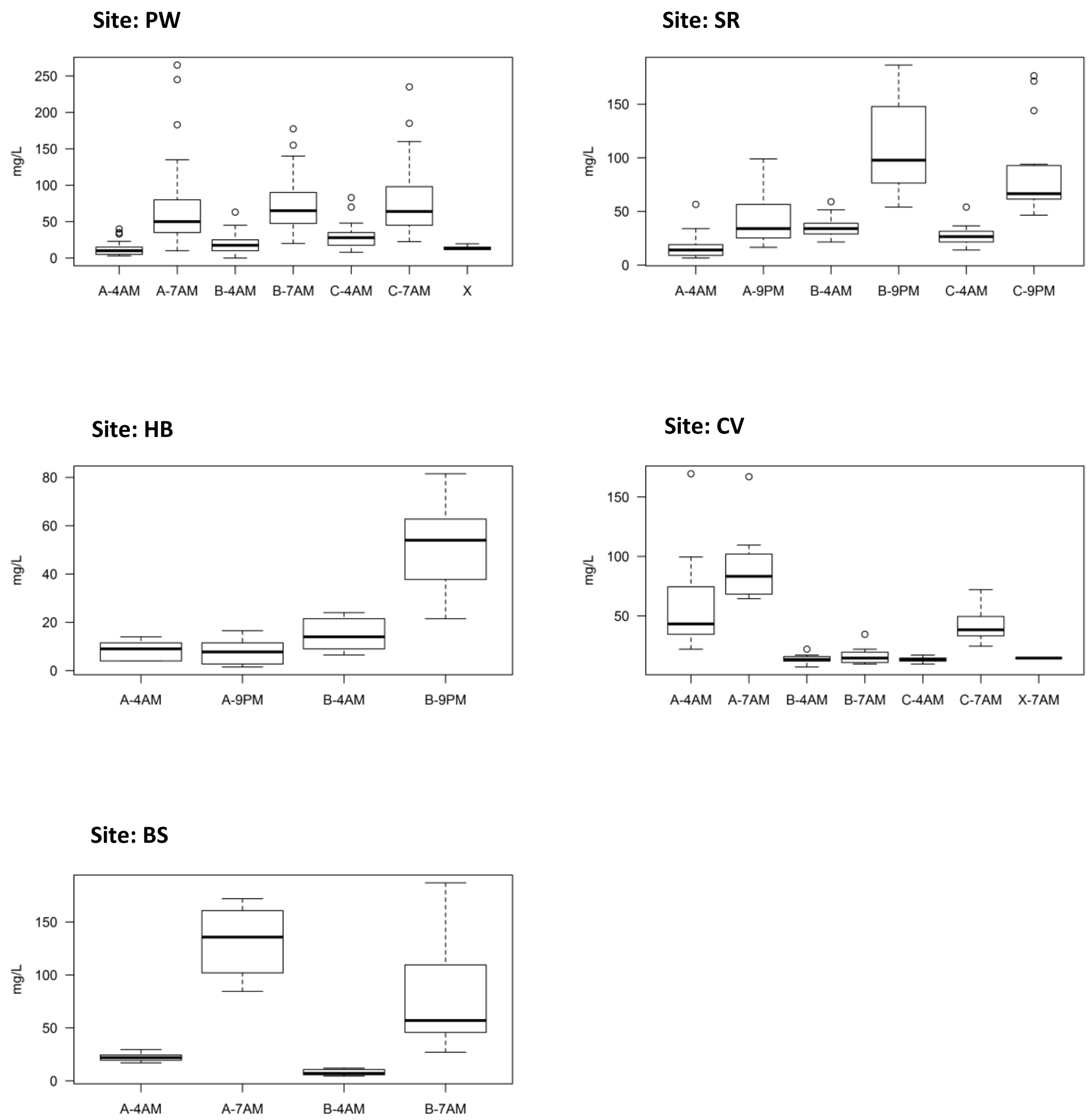


Figure 33 Boxplots showing COD (mg/L) concentrations for each site, by sample point and time period. COD in sewers is significantly higher during the daytime samples than at the night-time minimum. Watercourse samples do not significantly vary day and night, as expected. The exception is at site PW, where the COD at the watercourse inflow (C) is elevated during the daytime – evidence of contamination by misconnections.

4.4 *Discussion*

4.4.1 Major ion water typing method

This study has shown that water typing can differentiate captured flows from wastewaters in combined sewers, and in some cases approximately quantify this. Its successful application was demonstrated in locations where end-point water types of the groundwater (feeding the captured streams and springs) and wastewater could be adequately determined. Major ion water typing can differentiate sources of water even amid the short term variability in wastewater chemistry.

The method is most suited to confirming stream and spring capture where it is in the form of a discrete inflow. Capture by interception – a direct inflow of an open or culverted watercourse into an intercepting combined sewer (Chapter 2) – is one form of capture. Of the five sites in Sheffield tested in this study, three were this form of capture.

4.4.2 Limitations of major ion water typing

There are two important issues with the major ion water typing method that may limit its applicability. The first is the requirement to sample the end-points to type them, and the fact that it is not always possible to reliably do so. The results suggested that where end-points could not be sampled individually, the watercourse type could not be confidently predicted from nearby springwater samples, owing to the considerable local heterogeneity in geology and chemistry. This is most likely explained by the springwaters of Sheffield being sourced from a mixture of shallow groundwater and local soilwater, both of which have high spatial heterogeneity across the catchment, and whose chemistry is influenced by the complex geological strata and urban contaminants. A key limitation is therefore that major ion water typing cannot at this stage be confidently used to detect captured watercourses where discrete inflows are not known (such as for capture by conversion or direct spring capture, or indeed for infiltration-inflow), where the end-points cannot be independently typed or predicted *a priori*. This could be a significant barrier: there may be some evidence of a lost watercourse having at some point been converted into a combined sewer, with no known discrete inflows to sample. Where there is a discrete inflow, dye testing could confirm capture through connectivity much more easily than the water typing method. In catchments where the geology is less spatially varied, it might be possible to more precisely type springwaters and predict the captured water end-point, making the method much more reliable. This could be explored by testing the method in a different catchment with simpler and more predictable geology than Sheffield. An appropriate catchment must also be one where there is a sufficient chemical difference between tapwaters and springwaters, such as in Sheffield where the local groundwater is not used in the drinking water supply. Groundwater characterisation may have been improved by sampling from local boreholes rather than from springs and seeps that may have been mixed by various surface water contaminants, and this may also be appropriate in catchments with more uniform water table properties.

The second issue is the requirement for sufficient samples to confidently determine the water types amid the variability in chemistry, in respect to both spatial and temporal variability. Given the difficulty in confidently predicting the springwater and wastewater end-points in Sheffield, the major ion water typing method is thus a comparative one. A single spot sample from a single point in the sewer at day and night would not be sufficient to confidently determine whether it contains captured water without establishing the local mixing line of typical wastewater (which was often found to be a distinctive type, but not predictable from the local tapwater) and groundwater (difficult to sample if the source of capture is unknown, and not easily predicted from nearby springs). Individual site-by-site consideration, as well as careful location of sampling points, would be essential for applying this method. Even with these conditions satisfied, differentiation between some captured waters and wastewater was difficult in this study, due to their similar water types, or the considerable short-term variation in chemistries. This means that a single spot sample from sewers would not reliably type the waters to confidently predict capture by itself. As used in this study, multiple spot samples would be required within a short time period to establish the typical chemistry. Continuous auto-sampling throughout the day and night, though not possible in this study, may have confirmed the diurnal pattern in chemistries. It also would not have relied on the assumption that the chosen sampling time periods (around 4 a.m. for the night-time minimum and around 7 a.m. or 9 p.m. for the daytime) would reflect the true night-time minimum or daytime peaks, and so it may have resulted in a more robust and repeatable sampling method.

4.4.3 Applicability to detecting infiltration-inflow and other methods

Captured streams and springs can be the same water as from groundwater infiltration-inflow through pipe cracks and joints (i.e. shallow groundwater and soilwater) but with a different entry mechanism and pathway (such as via surface watercourses) that may expose it to different contaminants. In locations where groundwater could be more reliably typed than in this study, there is an opportunity to apply the major ion water typing method to detect infiltration-inflow. It is important to note that the coincidental effect of infiltration-inflow on the results in this study cannot be ruled out – extensive CCTV surveys were not possible to rule out visible signs of leakage into the sewers.

Pollutant-hydrograph methods typically assume concentrations of 0 mg/L COD in infiltration-inflow waters. This may be inappropriate for applying to captured streams and springs; this study demonstrated that while captured waters were relatively clean, they could still increase COD concentrations due to sewer misconnections or other contamination. This puts the major ion water typing at some advantage over pollutant-hydrograph methods: it does not require a unique marker to be absent in captured waters, but relies instead on relative proportions of ubiquitous and conservative major ions. If the end-points can be adequately determined through appropriate sampling, or could be predicted in catchments with less complex hydrogeology, major ion water typing may offer another option for detecting infiltration-inflow.

Furthermore, as identified at site PW, water typing could identify the mixing of a captured watercourse with a mains water burst, which have different water types but similarly low COD.

4.4.4 Use of minor ions and metals in water typing

Minor ions offered additional insight into discriminating water types. While there were no unique markers of captured waters that were not also present in wastewaters, several metals were identified (probably of geological source) that were consistently higher in captured waters than wastewaters, and others (probably of domestic wastewater origin) that were consistently lower in captured waters than wastewaters. They may offer additional corroboration to the major ion water typing to differentiate water types.

4.4.5 Implications for the water industry

This study confirmed that captured streams and springs do enter the combined sewer system in Sheffield, but was not able to confirm all sites of capture (those without discrete inflows). Where capture is suspected, major ion water typing may be able to provide direct detection to confirm this.

At a network scale, this study is not yet able to quantify the total volume of baseflow of captured streams and springs to the WwTW. However, at one site, a combined sewer consists almost exclusively of captured water at the night-time minimum, and a substantial 60-90% captured flows during the daytime. Stream and spring capture could therefore be contributing locally significant amounts of clean baseflow (in addition to rainfall runoff associated with the former watercourse catchments) to the combined sewers. Where existing capacity is limited, this could increase the likelihood of sewer flooding or CSO spills – both of which are of serious concern for the water industry.

Captured streams and springs in combined sewers, along with further development of methods to identify them, should therefore be taken seriously by the water industry, along with groundwater infiltration-inflow, for managing local and network capacity, flood risk and combined sewer overflows, and reducing the baseflow to the WwTW.

4.4.6 Comment on timing of sampling programmes

The springwater and tapwater characterisations and the sewer capture sampling programmes were undertaken at different times between April 2012 and November 2013. This introduces uncertainty over long term chemistry changes in spring and tap waters that may influence the interpretation of the results during the sewer capture sampling. For example, the blend of tapwaters supplied to the area may be altered as water resources and treatment processes are adjusted, with consequent effects on wastewater chemistry. However, the sampled tapwater chemistries were broadly consistent with the tapwater chemistries reported in 2004 in documents provided by Yorkshire Water (James Kitson, Yorkshire Water, pers. comm. May 2012). Similarly, there may be seasonal fluctuations in groundwater chemistry associated with water contact with different geological strata, or there may be isolated pollution incidents. Again, it is expected that any changes in spring chemistries would be minor, as they are broadly consistent with the range of spring sample chemistries undertaken years previously by Banks (1997).

The ideal sampling programme would have conducted all sampling concurrently to rule out any chemical changes in water chemistry in springs, tapwaters and wastewaters. However, this was a limitation of this study: evidence from each sampling programme was required to develop the case for Yorkshire Water to allow access to the sewer network. This included an unpublished pilot of the water typing method at Blackburn Meadows WwTW on the wastewater influent to demonstrate the wastewater sample handling and analysis. Due to the long term development of this sampling programme and requirement for permission from Yorkshire Water, this delayed the access to the sewer network until Autumn 2013, and there was no flexibility to alter sampling dates around dry weather. Furthermore, there were insufficient resources to undertake all springwater and tapwater samples again at the same time. Such limitations would be important to consider if this method were reapplied, and given the resources it would be strongly recommended to undertaken concurrent sampling for the avoidance of uncertainty of long term chemistry changes, or the development of suitable error bounds to account for seasonal or long term fluctuations.

4.5 Conclusion

Major ion water typing can detect the mixing of captured streams and springs in combined sewers, though with varying success. It requires captured waters to be a distinctly different water type to the local wastewater, for these end-points to be reliably typed, and for sufficient sampling locations to enable a comparative assessment. In practice, such requirements may be difficult to satisfy, particularly for this case study in Sheffield where considerable geological heterogeneity gives rise to difficulty in typing the local springwater end-points.

Lost watercourses captured into combined sewers by interception are discrete inflows, and the effectiveness of major ion water typing to detect these cases was satisfactorily demonstrated, in some respects potentially more reliably so than COD-based pollutant-hydrographs which assume negligible COD in captured waters or infiltration-inflow. Other lost watercourses have been converted into sewers, and lost springs have been directly drained to sewers. In these cases there are no discrete inflows, so it is difficult to sample the end-points for typing, and major ion water typing cannot be confidently used for detecting these. Given the difficulty in locating such lost watercourses where no discrete point of capture exists, this method is not likely to be an ideal solution to detecting whether or not they have been captured into the sewer system.

5 Predicting stream and spring capture and infiltration-inflow to combined sewer networks using an expert knowledge Bayesian Belief Network

5.1 Introduction

Stream and spring capture is a source of clean baseflow to combined sewer systems, in addition to infiltration-inflow. Multiple lines of evidence are required to indicate stream and spring capture, from desk-based methods to more expensive field tests using water chemistry or connectivity testing (Chapter 3). It would be of benefit to the water industry to develop a model that predicts the presence of stream and spring capture to combined sewers, enabling areas of the network to be targeted for further tests to confirm or eliminate them from enquiry. By also predicting the presence of infiltration-inflow, the model would serve as a useful source of information to understand how stream and spring capture, a relatively little understood concept, affects combined sewer networks and compares to the much more widely known infiltration-inflow.

Development of numerical hydrodynamic models of infiltration-inflow has been undertaken in other studies (Karpf et al. 2011), but modelling the physical hydraulic processes would be too complex and demanding for a network-scale assessment for use by the water industry. Empirical models have been developed that link sewer characteristics with sewer condition, pipe degradation or infiltration-inflow (Erskine et al. 2014, Karpf and Krebs 2011, Scholten et al. 2014, Wright et al. 2006). Such data-driven approaches inevitably suffer from a lack of data, which is especially the case when predicting the new and relatively unobserved stream and spring capture.

Bayesian Belief Networks (BBNs) are directed acyclic graphs that relate random variables to other random variables by nodes connected by directed links (Charniak 1991). Parent nodes link to child nodes, indicating a relationship between the two. The relationship may be that the parent causes the child or that the child is an approximate observation of the parent, for example (Charniak 1991). The graph is acyclic because feedback loops are not possible (Uusitalo 2007), though some studies have identified workarounds for this (e.g. Kumar et al. 2008). Variable nodes have a range of possible values (states), which can be discrete or continuous. The relationships between variables are given as known prior probabilities in conditional probability tables (CPTs) for each node. The BBN uses probabilistic inference of Bayes' Rule to calculate the conditional posterior probabilities (beliefs) of unobserved variables given observed states (evidence) of some or all other variables. It is therefore possible to calculate the probability of the state of a variable *A* from the observed state of a variable *B*. Additionally, given an observed state of variable *A*, the likely state of variable *B* to have caused that can be calculated.

In Bayesian statistics, probability measures the degree of belief or uncertainty; this is fundamentally different to frequentist statistics where probability measures the expected proportion of outcomes (Gelman et al. 2004). Uncertainty about the strength of the relationships between variables is thus explicitly incorporated into BBNs via the assignment of probabilities in the CPT, making this one of the key strengths of a Bayesian approach to statistics (Gelman et al. 2004). BBNs are also able to predict the value of a variable where some or all of the variable states are unknown, by reverting to the underlying prior probability distribution. The direct inclusion of uncertainty, transparency of the modelling process, and flexibility in use make BBNs powerful tools for data poor and decision management applications, and they have found particular use in ecological and environmental management fields (e.g. Borsuk et al. 2004, Marcot et al. 2006, McCann et al. 2006, Uusitalo 2007).

The prior probabilities can be parameterised by the modeller from the literature, from limited available data, from expert knowledge, or a combination of these (Charniak 1991, Chen and Pollino 2012, Scholten et al. 2013). Use of expert beliefs is particularly important in fields where there are limited data but considerable informal and undocumented knowledge among researchers or practitioners (Drescher et al. 2013). There is a growing literature base attempting to formalise expert elicitation procedures for use in BBNs. For BBN models to be accepted by decision makers, they must be transparent in their design and parameterisation, scientifically rigorous, and characterise and reduce uncertainties associated with the modelling and expert knowledge elicitation process, such as bias and heuristics (Burgman et al. 2006, Drescher et al. 2013, Uusitalo 2007).

A BBN tool to predict the likelihood of infiltration-inflow across sewer networks has previously been attempted as part of a project by UKWIR (2012). The author was a part of the team that delivered this. The scoping tool is now being used by water companies in the UK to identify areas at risk of infiltration-inflow (Paul Hurcombe, Severn Trent Water, pers. comm. November 2013). However, the model did not explicitly consider stream and spring capture within the definition of infiltration-inflow and there was not a robust validation of the model output against observed data. This presents an ideal opportunity to build on the existing study to address these issues, by incorporating additional relevant variables, improving the robustness of the model validation in light of new data, and explicitly predicting the likelihood of stream and spring capture.

The novel contributions of this study are the presentation of the BBN as a useful tool for the water industry and the results of the case study application to characterise and enhance understanding of stream and spring capture in relation to infiltration-inflow to combined sewer systems. The study therefore has the following objectives:

1. develop a tool using a BBN, validated against observed data, that can be used to predict stream and spring capture and infiltration-inflow to combined sewer networks from available desk-based evidence;
2. characterise and evaluate the state of expert knowledge on this subject;
3. identify how the relative likelihood of stream and spring capture compares with infiltration-inflow.

This chapter first describes the model development and expert elicitation process. It then applies the model to the case study of Sheffield, UK, to identify the likelihoods of and spatial differences between stream and spring capture and infiltration-inflow. Finally, it details the results of a multi-stage validation and sensitivity analysis process, discussing the confidence in the model, sources of uncertainty, opportunities for further development, and the implications this may have for the water industry.

5.2 Method

5.2.1 Expert engagement

Experts were defined as having particular experience in the fields of infiltration-inflow to sewer systems, urban drainage and historic watercourse management, stream burial and capture, or sewer network modelling. Twenty two experts agreed to participate. In order to reduce the influence of bias by selecting a particular community of experts, the group included representatives from research (universities) and practice (water companies, local authorities and consultancies), from both within the study catchment and beyond, and by selecting experts from the literature as well as by peer-recommendation and networking.

From this group, two pairs of experts were selected to take part in separate workshops for the model design stage (**Table 12**). All experts were invited to participate in the probability elicitation questionnaire, though only five completed this.

Table 12 Details of participating experts.

Expert	Type	Background	Workshop	Questionnaire
1	Consultancy	Urban drainage and sewers	Yes	
2	Water company	Sewer modelling	Yes	
3	Consultancy	Sewer modelling	Yes	Yes
4	Academic	Urban drainage and sewers	Yes	Yes
5	Academic	Urban drainage and sewers		Yes
6	Consultancy	Sewer condition modelling		Yes
7	Consultancy	Sewer modelling		Yes

5.2.2 Conceptual model design workshops

Two separate semi-structured workshops, each consisting of two experts plus the author, were arranged to design the model. The author acted as an impartial facilitator of the workshops, structuring the process and questioning the experts' choices, but not unduly influencing their opinions. The first step was to establish a common working definition of infiltration-inflow and stream and spring capture. There was initial divergence in expert interpretation of the sources and pathways of water contributing to infiltration-inflow. The interpretation of stream and spring capture was also initially inconsistent among the experts, reflecting the fact that this type of clean water entry to combined sewers has rarely been considered distinctly from infiltration-inflow. For the purpose of this study, it was important to differentiate stream and spring capture from infiltration-inflow. Infiltration-inflow was therefore defined as the unintentional ingress of clean waters into a combined sewer through pipe cracks and defective joints, from sources including groundwater, soil water and mains water supply pipe leakage. Stream and spring capture was differentiated as intentional inflows of clean water from streams or springs into the combined sewer system, and split into the three modes of entry defined in Chapter 2:

1. capture by conversion is the intentional historic replacement of a watercourse by a combined sewer, capturing the clean spring-fed baseflow at source, with no known discrete inflow;
2. capture by interception is the intentional discrete inflow of a watercourse into an intercepting combined sewer;
3. direct spring capture is the intentional drainage of shallow groundwater or springs, piped into a combined sewer (land drainage connected into combined sewers was considered by the experts to implicitly include this form of capture, but they were satisfied with this distinction).

The second step was a brainstorm of the variables influencing stream and spring capture and infiltration-inflow to combined sewer systems. Experts were asked to discuss the inclusion and the relative importance of the variables, with each workshop arriving at a consensus between the two experts present. They were then asked to group variables into related conceptual sets. For example, variables relating to sewer condition were divided into those affecting the proneness of the sewer fabric to defects and external factors that induce stress on the sewer.

The third step was to structure the model by drawing the relationship links between the identified variables and to qualify the anticipated relationships, for example specifying that increasing age is likely to result in poorer sewer condition. This was an iterative process, and any disagreement between the two experts resulted in discussion and revision of the most important variables.

In the final step, experts discussed variable discretisation. They were asked to consider what input data might be available for the variables, how categorical data might be grouped, and how continuous data might be most appropriately discretised into categories (such as sewer pipe age categorised into time periods of sewer construction, implicitly reflecting the various techniques and design changes).

Draft model structures were developed from each of the two workshops. At the end of the second workshop, the experts were shown the results of the first and asked to describe where they agreed or disagreed with the other group. The separate workshops had independently arrived at similar model structures and included most of the same variables, with only some very specific variables identified differently, such as sewer corrosion influencing sewer condition. The general consensus and agreement between and within the expert workshops suggests a common understanding of infiltration-inflow and stream and spring capture. This lends greater confidence to the derived model than if it had been designed from a single expert or solely by the author.

5.2.3 Final model design

The draft conceptual models were compiled into a final model structure by the author, retaining the common key variables and relationships that experts identified would influence captured streams and springs and infiltration-inflow. Some variables were removed in order to simplify the model structure, particularly those identified by only one of the expert groups, or those covering only specific concepts such as pipe corrosion influencing sewer condition and the presence of past mining activity influencing groundwater availability.

It is good practice in BBN development to keep the number of variables to a minimum and to keep the number of node levels (i.e. the number of nodes between the first, input nodes and the last, output nodes) to less than five (Chen and Pollino 2012). Simplifications were inevitable, but feedback from the experts on the final model structure and discretisation suggested no fundamental disagreement. The final model structure is shown in **Figure 34**, detailing the variables used and their relationship links with other variables.

For the purposes of this study, the model consists of two sub-networks. One predicts the likelihood of infiltration-inflow entering a particular sewer, given factors relating the sewer pipe condition, lateral pipe condition and the availability of water at the sewer. The second predicts the likelihood of stream and spring capture, given factors relating to the three types of capture previously outlined. The two sub-networks are joined by a deterministic node that predicts the combined probability of there being infiltration-inflow, stream and spring capture, both together, or neither.

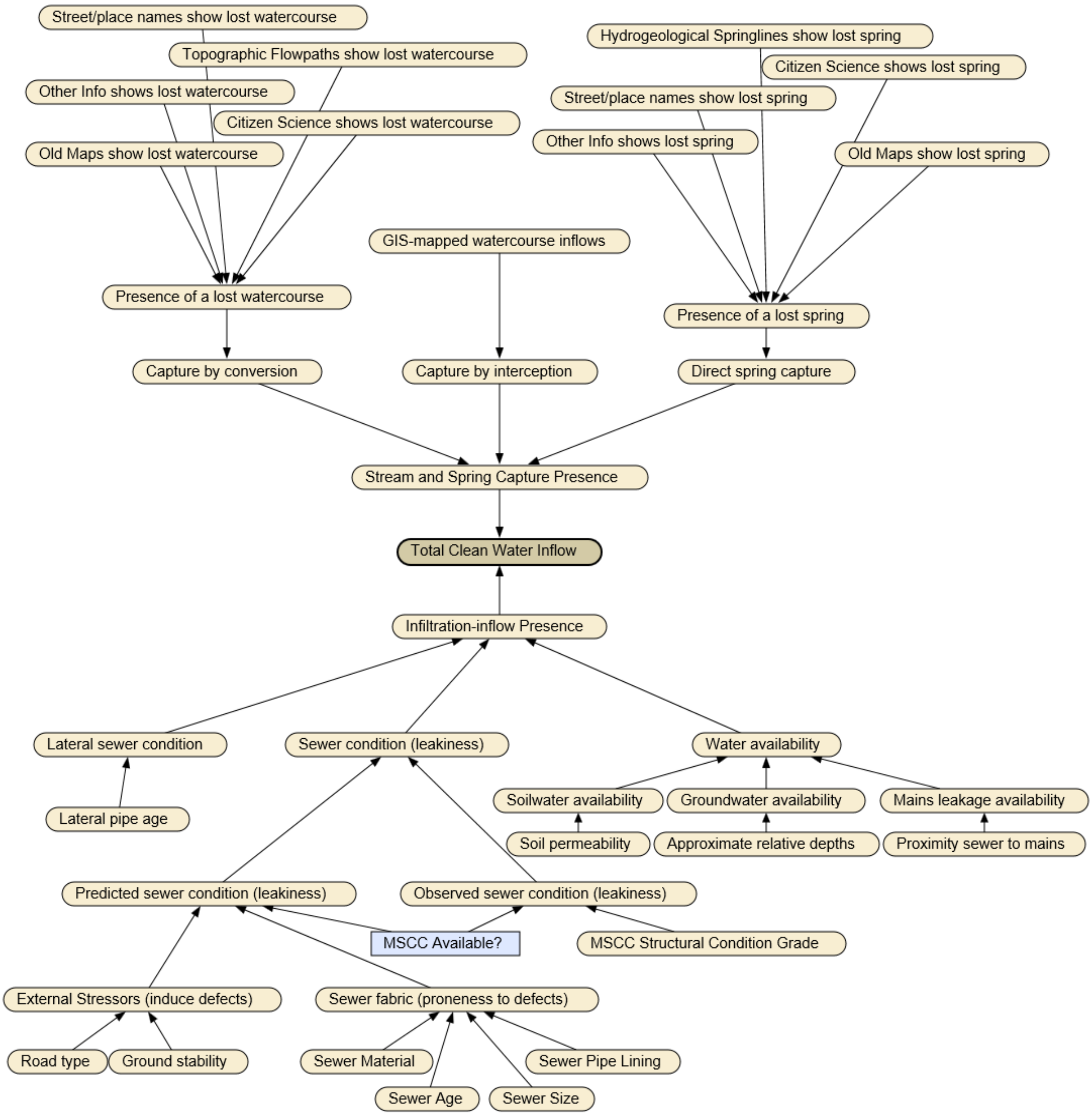


Figure 34 BBN model structure showing the variables and their relationships (shown as nodes and links between the nodes). Variable states are detailed further in **Table 16**.

It is useful to briefly compare the capture sub-network in **Figure 34** and the capture indication methodology flowchart that was derived from the work in Chapter 3 (**Figure 15**). For the BBN, experts identified variables that intentionally reflected the lines of evidence previously identified as being able to locate lost streams and springs (e.g. historical maps, topographical flowpath modelling), but stopped short of including variables reflecting lines of evidence that can be used to indicate or verify the presence of stream or spring capture (e.g. night-time minimum flows). Instead, the experts, in agreement with the author, considered it to be an acceptable simplification to encapsulate these additional variables implicitly within the jump from the presence of a lost stream or spring to the likelihood of capture being present. This reflected the intended purpose of the model as one that could use widely available data to assess whole sewer networks; night-time minimum flows, water typing or connectivity testing are more likely to be commissioned at a local scale on the basis on this first assessment.

Data sources identified in the expert workshops indicated that precise measured data would rarely be available. Variables were discretised into quantitative or qualitative categories (states) based either on values given from key data sources (e.g. ground stability was inferred from the ground stability summary in the British Geological Survey's SuDS Infiltration Map) or, where such data were unavailable, into subjective qualitative states (e.g. sewer condition, discretised simply as good, medium or poor). Subjective variable states can introduce inherent uncertainty in their interpretation by experts, but are justified when there is simply insufficient data or knowledge to attempt to quantify. For example, asking the experts to use sewer age, material, size and presence of pipe lining to predict the sewer condition in terms of a measureable quantity such as defects per length of sewer pipe may appear to afford the model a greater degree of precision than it is capable of, given the level of expert knowledge in the system.

The capture sub-network integrates the lines of evidence identified in Chapter 3, such as from old maps, street and place names, and topographic flowpath modelling. These are discretised simply as yes or no answers to reflect whether or not the evidence indicates a lost watercourse or spring, and can be left blank where inconclusive. Given evidence of a lost watercourse, a lost spring, or an apparent watercourse inflow to a combined sewer shown in the mapped data, the model then predicts the likelihood that capture is actually occurring. This reflects various uncertainties about the ability to verify or observe capture, expected inaccuracies in mapped data, the possible presence of unmapped culverts, or the possibility of watercourses and springs no longer flowing due to hydrological changes in the catchment.

The final output variables were discretised in the form of likelihoods that stream and spring capture or infiltration-inflow is present or absent, rather than predicting quantifiable amounts as flow rates or fractions of wastewater flow. This is an appropriate simplification in the context of the model purpose as a scoping tool to differentiate sewers with relatively higher or lower likelihoods of stream and spring capture and infiltration-inflow.

A decision node was incorporated in a special case in order to allow CCTV-survey data to be inputted directly as Manual of Sewer Condition Classification (MSCC) Sewer Condition Grade scores, a format widely used by water companies and available for some sections of sewer. Because experts had expressed that MSCC scores are the best, direct indicator of sewer condition, the decision node allows this data, where available, to override the predicted sewer condition derived from sewer fabric and external stressor factors in an attempt to improve upon the predictive accuracy. Studies have shown, however, that MSCC scores cannot be easily and directly predicted from pipe characteristics (Chughtai and Zayed 2008, Egger et al. 2013).

5.2.4 Model parameterisation

CPTs assigned to each model node in BBNs can be derived from available data, or can be elicited from expert knowledge where insufficient data exists – a common issue in environmental or new fields such as this (e.g. Chen and Pollino 2012). The ability to use expert knowledge is particularly appropriate in this study, where stream and spring capture is a relatively new concept that is largely untested, where experts may have considerable subjective and objective knowledge from experience that has not yet been translated into published data or studies. Subjectivity in expert knowledge does, however, introduce uncertainty (e.g. bias, heuristics) and presents challenges in robustly measuring (*encoding*) expert beliefs as probabilities to use in the model. Without steps to address this subjectivity, BBNs parameterised by expert knowledge “may be perceived as subjective or ‘unscientific’ and can reduce model acceptance by scientists and/or policy makers” (Landuyt et al. 2013: 8). It is particularly important to reduce the uncertainty introduced through the elicitation process itself, which can mask the genuine expert uncertainty about the system in question. Recommendations from literature across a range of fields include: applying a repeatable methodology; minimising sample bias by eliciting viewpoints from a sufficient number of experts; minimising cognitive demand on the experts by reducing the number of questions; using clearly defined terms to reduce linguistic uncertainty; eliciting estimates in an appropriate manner; characterising the central viewpoints, variation and self-confidence among experts; and aggregating the experts' answers fairly (Burgman et al. 2006, Drescher et al. 2013).

A questionnaire was used to ask experts to estimate the probabilities for each state of a child node based on given states of the parent variables. The experts' uncertainty about the system and about how accurately the model and variables describe the system is therefore characterised directly through the values and distribution of the probabilities given. The full questionnaire is provided in Appendix E and the general approach is described here.

As the number of parent variables and number of possible states for each variable increase, the size of the conditional probability space exponentially increases (Das 2004). This makes it unfeasible to elicit probabilities for every combination in the model. To reduce the number of questions asked, the questionnaire was designed to elicit probabilities for a small number of combinations and then interpolate the remaining probabilities from these as proposed by Das (2004) and further developed by Kumar *et al.* (2013). The expert workshops had already described the expected relationships between variables, and this was used by the author to select *compatible* combinations for each CPT, i.e. representing all parent nodes together in the most extreme states and some nominally mid-way scenarios (**Table 13**). Rather than a straightforward linear interpolation to complete the CPT, non-linearity was identified by eliciting answers for *critical* combinations of parent node states (**Table 14**). For the *critical* cases, the experts were asked to estimate how the probability of the child node being in particular states would change from initial values if the states of just one parent node changed with all other parent nodes remaining the same. The initial values were taken from each expert's answers to the previous *compatible* probability questions. The relative change in probabilities measures whether a critical variable state or critical combination of variable states results in a significant threshold response. The importance of the parent variables in explaining or causing the child variables was also elicited (**Table 15**), and this was used as a weighting in the interpolation. This critical probability approach greatly improves the elicitation efficiency by reducing the number of questions that experts have to consider (Kumar et al. 2013).

Probabilities were elicited as percentage scores distributed between the variable states (**Tables 13-15**). Other studies have elicited expert beliefs as direct values of the variable states with uncertainty ranges by three-point estimation (most likely, maximum and minimum expected) or by variable interval methods (median and quartiles) (UKWIR 2012, Usher and Strachan 2013). The chosen approach reflected the fact that it would be more intuitive and appropriate to estimate probability distributions over the qualitative variable states.

Table 13 Example of compatible probability elicitation in the questionnaire, shown for the child variable *Predicted Sewer Condition* (poor, medium or good states) given parent variables *Sewer Fabric* and *External Stressors*. The question wording is also provided for the expert for each line, reproduced here for line A-B-C.

Compatible probabilities		***Predicted Sewer Condition (Leakiness)***		
Sewer Fabric (Proneness To Defects)	***External Stressors (Induce Defects)***	**Poor**	**Medium**	**Good**
Highly prone	Highly defect inducing	A	B	C
Somewhat prone	Somewhat defect inducing	/100	/100	/100
Not really prone	Not really defect inducing	/100	/100	/100
"Given the fact that the *Sewer Fabric* is highly prone to defects and *External Stressors* are highly defect inducing, what is the likelihood that the *Predicted Sewer Condition* is either poor, medium or good? Assign likelihood as a score from 0-100, with each row adding up to 100."				

Table 14 Example of critical probability elicitation in the questionnaire, shown for the child variable *Predicted Sewer Condition* (poor, medium or good states) given parent variables *Sewer Fabric* and *External Stressors*. Lines A-B-C are taken directly from the values given in the compatible probability questions. The question wording is provided for each line.

Parent	**Possible States**	***Predicted Sewer Condition (Leakiness)***		
		Poor	**Medium**	**Good**
Sewer Fabric (Proneness To Defects)	Highly prone	A	B	C
	Somewhat prone	/100	/100	/100
	Not really prone	/100	/100	/100
External Stressors (Induce Defects)	Highly defect inducing	A	B	C
	Somewhat defect inducing	/100	/100	/100
	Not really defect inducing	/100	/100	/100
"If other parent variables remain the same (*External Stressors* remain highly defect inducing), in the states resulting in the highest likelihoods of infiltration-inflow, what is the impact of changing the *Sewer Fabric* state from highly prone to somewhat or not really prone on the probabilities that the *Predicted Sewer Condition* will be poor, medium or good? Assign a likelihood as a score from 0-100, with each row adding up to 100." "If other parent variables remain the same (*Sewer Fabric* remains highly prone to defects), in the states resulting in the highest likelihoods of infiltration-inflow, what is the impact of changing the *External Stressors* state from highly defect inducing to somewhat or not really defect inducing on the probabilities that the *Predicted Sewer Condition* will be poor, medium or good? Assign likelihood as a score from 0-100, with each row adding up to 100."				

Table 15 Example of variable weighting elicitation in the questionnaire, shown for the child variable *Predicted Sewer Condition* given parent variables *Sewer Fabric* and *External Stressors*.

Child	**Parents**	**Score of 'importance'**
Predicted Sewer Condition (Leakiness)	*Sewer Fabric (Proneness To Defects)*	/100
	External Stressors	/100
"How important are the parent variables *Sewer Fabric* and *External Stressors* in determining the *Predicted Sewer Condition*? Assign a score from 0-100 to show the relative and absolute importance of each – they do not have to sum to 100, and could be the same."		

The questionnaire was designed with internal consistency checks of the experts' answers to prompt when probability distributions did not sum to 100. The question wording was consistent and straightforward to reduce linguistic uncertainty, and experts were able to discuss queries over the telephone with the author. Experts were provided with summary and detailed descriptions of the model variables and the sources and reliability of input data available for each, as well as background information and diagrams to ensure they had a common understanding of the working definitions of infiltration-inflow and stream and spring capture for this study. They were asked to score their own self-confidence for the infiltration-inflow set of questions and the stream and spring capture questions, to explicitly capture their confidence about the system in question. The experts' answers were averaged and weighted according to their self-confidence scores, and non-linearly interpolated to fill the CPTs with respect to the compatible and critical probabilities; this procedure was completed by Kumar.

The infiltration-inflow sub-network includes some incompatible variable state combinations that do not occur in sewer networks (UKWIR 2012). The following were therefore excluded from the questionnaire and removed from the interpolation:

- clay pipes in the 900 to 1500 or 1500 to 3500 mm size categories at any age;
- plastic pipes in the 900 to 1500 or 1500 to 3500 mm size categories earlier than the 1991-2014 age category;
- brick sewers in the 0 to 300 mm size category at any age;
- brick sewers later than the 1946 to 1964 age category in any size.

Of the 22 experts that agreed to participate, just five completed the questionnaire (refer back to **Table 12**). Drescher *et al.* (2013) suggest no fixed requirement on the minimum number of experts required, with it depending on the subject matter and study. Stream and spring capture is a relatively new concept; no participants claimed to have expertise specifically on this subject, instead drawing on their wider knowledge and experience of infiltration-inflow and sewer networks. The questionnaire took over an hour to complete in most cases – there was no compensation or reward for expert participation, and the demand on the experts' time may have contributed to the high attrition rate, which is a common issue in developing BBN models from expert knowledge (Drescher et al. 2013).

The complete CPTs were then compiled in Netica (Norsys Software Corp., www.norsys.com) by Kumar, using Bayes' theorem to calculate the probability for every node in the model.

5.2.5 Model testing

The model was tested to check that it behaved as expected, focusing on errors and plausibility rather than predictive accuracy. The effect of changing the state of each variable in combination with another was tested systematically. Hypothetical scenarios were also developed to test the plausibility of the model response to extreme and typical conditions, and selected experts were asked to provide feedback on whether the model predictions were plausible. Hypothetical scenarios ranged from highly degraded sewers in wet conditions to high quality, watertight sewers in areas with low water availability, specifying node states accordingly.

In most cases, the model reproduced the basic relationship patterns as described by the experts during the two model design workshops. Unexpected discontinuities in the response of calculated probabilities to changing variable states can be a sign of modelling error rather than the experts' genuine beliefs of a critical variable combination. For example, in some instances the experts had interpreted the critical probability questions incorrectly, leading to the predicted likelihood of infiltration increasing as water availability was changed from "low" to "high", but decreasing unexpectedly in the "medium" state. Such issues were amended by re-interpolating the experts' probabilities linearly, i.e. without critical probabilities, as this was considered to better represent the true beliefs of the experts.

In most cases the agreement among experts was good with regard to the overall trend, but poor with regard to the specific probability values assigned. The process of averaging the expert probabilities has the effect of flattening the probability distributions and reducing the model sensitivity. In some cases, a single expert was removed from the calculation where their results were perceived by the author to be implausible or wildly inconsistent with the other experts. The self-assessed confidence scores (0 to 100) were significantly higher for the infiltration-inflow questions (mean 60; $\sigma=10.9$; $n=5$) than the stream and spring capture questions (mean 39; $\sigma=16.2$; $n=5$); using a two-sample t-test, $p<0.043$. This suggests that the experts had less confidence in predicting stream and spring capture than infiltration-inflow.

5.3 Model application to case study catchment

5.3.1 Model input data

Available data were gathered in a spatial format using a geographical information system (GIS). Sewer network data were supplied in GIS format by Yorkshire Water for the study area. Each model variable was added as a field to the GIS attribute table database, and values for each variable were added for every segment of sewer pipe in the network. **Table 16** details the data sources, discretisation and calculation methods for each variable used in the infiltration-inflow and stream and spring capture sub-networks.

For each segment of sewer in the sewer network database, the available input data for each variable were entered with the states where known, generating a case file containing the known input values for each sewer segment. Blanks were left for all missing or unknown data (some variables such as sewer pipe age had less than 1% data coverage). The ability of the BBN to handle missing data by assigning the general probability distribution to the blanks is one of the key strengths of this method.

Netica was used to process the case file and report the calculated probabilities for the presence and absence of infiltration-inflow and stream and spring capture for each sewer segment in the network. This was then exported back into GIS for mapping and analysis. A full copy of the model is provided in Appendix F.

Table 16 Model variable definitions, states and data sources.

Variable	Type	Data source / parent nodes	States (and other notes)
Infiltration-inflow sub-network			
Sewer Material	Discrete	Sewer Network Data.	Brick; Clay; Concrete; Plastic. These four are the most common material types, and other materials are left blank. 30% data coverage.
Sewer Age	Discrete	Sewer Network Data.	1800 to 1919; 1920 to 1945; 1946 to 1964; 1965 to 1979; 1980 to 1990; 1991 to 2014. Categories based on age groupings in sewer network data. 1% data coverage.
Sewer Size	Continuous	Sewer Network Data.	0 to 300 mm; 300 to 900 mm; 900 to 1500 mm; 1500 mm and greater. Non circular pipe shapes given as average of available dimensions. 31% data coverage.
Sewer Pipe Lining	Discrete	Sewer Network Data.	No; Yes. >99% data coverage.
Sewer Fabric (Proneness To Defects)	Discrete	*Sewer Material*; *Sewer Age*; *Sewer Size*; *Sewer Pipe Lining*.	Highly prone; Somewhat prone; Not really prone.
Road Type (Traffic Loading)	Discrete	Ordnance Survey Vectormap Local.	A/B primary or trunk road; Minor road; Local street or smaller. Reclassified to three categories. 23% data coverage.
Ground Stability	Discrete	British Geological Survey SuDS Infiltration Map (ground stability summary).	Very significant geohazard; Significant potential for geohazard; Potential geohazard; Geohazard unlikely. Directly taken from SuDS Infiltration Map categories. 100% data coverage.
External Stressors (Induce Defects)	Discrete	*Road Type*; *Ground Stability*.	Highly defect inducing; Somewhat defect inducing; Not really defect inducing.
Predicted Sewer Condition (Leakiness)	Discrete	*Sewer Fabric*; *External Stressors*.	Poor; Medium; Good.
MSCC Available?	Decision	CCTV survey results supplied by Yorkshire Water.	True; False.
MSCC Structural Condition Grade	Discrete	CCTV survey results supplied by Yorkshire Water.	5; 4; 3; 2; 1. Scores relate to widely used MSCC grading, from worst structural condition (5) to best (1). 13% data coverage.

Variable	**Type**	**Data source / parent nodes**	**States (and other notes)**
Observed Sewer Condition (Leakiness)	Discrete	*MSCC Structural Condition Grade*.	Poor; Medium; Good.
Sewer Condition (Leakiness)	Discrete	*Predicted Sewer Condition*; *Observed Sewer Condition*.	Poor; Medium; Good. Taken from Observed sewer condition (leakiness) when MSCC Available? is True. Taken from Predicted sewer condition (leakiness) when MSCC Available? Is False.
Soil Permeability	Discrete	Soilscapes (National Soil Resources Institute, Cranfield).	High; Medium; Low. Soilscape drainage and soil type descriptions classified into high, medium and low soil permeability states: 6=High; 16=Medium; 17=Medium; 20=Low. 97% data coverage.
Soilwater Availability	Discrete	Soil permeability.	Available; Unavailable.
Groundwater Approximate Relative Depth	Discrete	British Geological Survey SuDS Infiltration Map (depth to water table) (Dearden et al. 2013).	Groundwater likely above invert; Groundwater likely level with invert; Groundwater likely below invert. Sewer network data has many missing or possibly erroneous sewer invert depths, so depth to water table simplified as assumed relative depths taken from SuDS Infiltration Map: >5m below ground surface = GW_likely_below_invert; 3-5m below ground surface = GW_likely_level_with_invert; <3m below ground surface = GW_likely_above_invert. 100% data coverage.
Groundwater Availability	Discrete	*Groundwater Approximate Relative Depth*.	Available; Unavailable.
Proximity Of Sewer To Mains	Discrete	Sewer Network Data; Yorkshire Water Clean Supply Network.	Less than 10m from mains; Greater than 10m from mains. Distance calculation from centre of sewer segment line to nearest clean supply pipe line centre. 31% data coverage.
Mains Leakage Availability	Discrete	*Proximity Of Sewer To Mains*.	Available; Unavailable.
Water Availability At Sewer	Discrete	*Soilwater Availability*; *Groundwater Availability*; *Mains Leakage Availability*.	High; Medium; Low.

Variable	Type	Data source / parent nodes	States (and other notes)
Lateral Pipe Age	Discrete	National Building Class (Landmap).	1800 to 1919; 1920 to 1945; 1946 to 1964; 1965 to 1979; 1980 to 1990; 1991 to 2014. Lateral pipes assumed to be explained by property age, inferred from the nearest known property age. Categories reclassified to match data. 0 = blank 3 = 1800 to 1990 4 = 1920 to 1945 5 = 1946 to 1964 6 = 1965 to 1979 7 = 1980 to 1990 8 = 1991 to 2014 20% data coverage.
Lateral Condition	Discrete	*Lateral Pipe Age*.	Poor; Medium; Good. Simplified representation of lateral pipe condition from inferred age, acknowledging very limited availability of data to water companies.
Infiltration-inflow Presence	Discrete	*Sewer Condition (Leakiness)*; *Lateral Pipe Condition*; *Water Availability At Sewer*.	Present; Not Present.
Stream and spring capture sub-network			
Old Maps Show A Lost Spring; *Old Maps Show A Lost Watercourse*	Discrete	Ordnance Survey Mastermap; Manually reconstructed map of lost watercourses and springs from old maps.	Yes; No. Sewers marked as yes if they pass within 30 m distance from a lost watercourse or spring shown on historical maps. Data can only positively identify, so those not "yes" left blank. Springs – 1% data coverage. Watercourse – 4% data coverage.
Street/Place Names Show Lost Spring; *Street/Place Names Show Lost Watercourse*	Discrete	Ordnance Survey Gazetteer, Vectormap Local and manual search.	Yes; No. Sewers marked as yes if they pass within 30 m distance from a lost watercourse or spring shown on historical maps. Data can only positively identify, so those not "yes" left blank. Springs – 1% data coverage. Watercourse – 3% data coverage.

Variable	Type	Data source / parent nodes	States (and other notes)
Citizen Science Reports Of Lost Spring; *Citizen Science Reports Of Lost Watercourse*	Discrete	Manually collated data from the public.	Yes; No. Sewers marked as yes if they pass within 100 m distance (to reflect lower spatial precision of reports) from a lost watercourse or spring shown from citizen science reports. Data can only positively identify, so those not "yes" left blank. Springs – 2% data coverage. Watercourse – <1% data coverage.
Other Information Shows Lost Spring; *Other Information Shows Lost Watercourse*	Discrete	Manually collated data from books, records, paintings etc.	Yes; No. Sewers marked as yes if they pass within 100 m distance (to reflect lower spatial precision of information) from a lost watercourse or spring shown from other information. Data can only positively identify, so those not "yes" left blank. Springs – 1% data coverage. Watercourse – <1% data coverage.
Hydrogeological Springlines Show A Lost Spring	Discrete	BGS 1:50,000 Geology maps.	Yes; No. No reliable spatial correlation between spring location and geological strata at the scale of data available, reflecting numerous unmapped bands of strata in this area.
Presence Of A Lost Spring	Discrete	*Old Maps Show Lost Spring*; *Street/Place Names Show Lost Spring*; *Citizen Science Reports Show Lost Spring*; *Hydrogeological Springlines Show Lost Spring*; *Other Information Shows Lost Spring*.	Indicated; Not indicated.
Direct Spring Capture	Discrete	*Presence Of A Lost Spring*.	Actually captured; Not actually captured. Directly testing the expected likelihood of capture given a lost spring.
Topographic Flowpaths Show Lost Watercourse	Discrete	Modelled using ArcGIS HydroTools from Ordnance Survey Land-Form Profile DTM.	Yes; No. Sewers marked as yes if they pass within 30 m distance from a lost watercourse shown from topographic flowpaths. Data can only positively identify, so those not "yes" left blank. 20% data coverage.

Variable	Type	Data source / parent nodes	States (and other notes)
Presence Of A Lost Watercourse	Discrete	*Old Maps Show Lost Watercourse*; *Street/Place Names Show Lost Watercourse*; *Citizen Science Reports Show Lost Watercourse*; *Topographic Flowpaths Show Lost Watercourse*; *Other Information Shows Lost Watercourse*.	Indicated; Not indicated.
Capture By Conversion	Discrete	*Presence Of A Lost Watercourse*.	Actually captured; Not actually captured. Directly testing the expected likelihood of capture given a lost watercourse.
GIS-mapped Watercourse Inflow	Discrete	Sewer network data; Sheffield City Council map of culverted watercourses; Manual search.	Yes; No. Sewer marked as having watercourse inflow where sewer touches the boundary of a culverted watercourse. Data can only positively identify inflows, so those not "yes" left blank. <1% data coverage.
Capture By Interception	Discrete	*GIS-mapped Watercourse Inflow*.	Actually captured; Not actually captured. Directly testing the expected likelihood of capture given a mapped watercourse inflow.
Capture Presence	Discrete	*Direct Spring Capture*; *Capture By Conversion*; *Capture By Interception*.	Present; Not present.

5.3.2 Model results for case study catchment

The model output is colour-coded to differentiate the highest and lowest likelihoods of infiltration-inflow and stream and spring capture (**Figure 35** and **Figure 37**). The maps show that the pattern of predicted highest infiltration-inflow presence does not closely correspond with the highest capture risk. This reflects the expectations from the expert beliefs in the model design, variable selection and belief elicitation that stream and spring capture occurs due to a different set of processes. While infiltration-inflow presence has some localised clusters, it is generally far more spatially distributed across the sewer network than predicted stream and spring capture. Stream and spring capture is not closely spatially correlated with infiltration-inflow.

Individually, both infiltration-inflow and stream and spring capture likelihoods are spatially autocorrelated, with a less than 1% chance that the clusters observed between similar likelihoods could be the result of random chance (Global Moran's I) (Mitchell 2005). The Getis-Ord Gi* statistic was used to map the location of hot-spots (clusters of higher likelihoods) and cold-spots (clusters of lower likelihoods) using inverse distance weighting (Mitchell 2005) (**Figure 36** and **Figure 38**). This is particularly useful to illustrate how stream and spring capture is likely to be far more spatially clustered than infiltration-inflow and can occur in sewers predicted to have low infiltration-inflow likelihoods. Scoping of elevated stream and spring capture or infiltration-inflow likelihood in areas of the sewer network rather than individual sewers could be particularly useful for water companies to strategically target high risk areas for further on-site investigation or evaluate management options.

It is not straightforward to quantify the number of sewers likely to be experiencing stream or spring capture compared to infiltration-inflow; the model output in likelihoods, together with the narrow range and generally low values of probabilities, mean that there is no obvious or robustly defendable threshold to differentiate affected and unaffected sewer segments. The probabilistic approach of this BBN model is therefore both a strength and a weakness.

To resolve this issue, the modelled probabilities were ranked and indexed on a scale of 0 to 100, thus re-interpreting the model outputs as relative likelihoods rather than absolute. A comparison can then be made on the length or proportion of sewers above thresholds of this ranked index (**Table 17**). In the top 10% of this relative scale, infiltration-inflow affects 2.9% and stream and spring capture affects 0.2% of the combined sewers by length. In the top half of this relative scale, infiltration-inflow affects 27% and stream and spring capture affects 0.88% of the network by length. Stream and spring capture thus is likely to occur in a smaller proportion of the network, and is highly localised. This does not imply that stream and spring capture is less important than infiltration-inflow. While it may affect a smaller number of sewers rather than being a widely distributed problem, it is not yet possible to estimate the total volume of water it contributes at a network scale or at a localised scale. For this, the identified sites should be tested to confirm or eliminate the presence of capture and attempts made to quantify it, using techniques identified in Chapter 3.

Table 17 Affected length and proportion of sewer network (total 1730 km) affected by infiltration-inflow and stream and spring capture at different thresholds of the ranked modelled data.

Threshold	Infiltration-inflow by length (km)	Stream and spring capture by length (km)
>90th %ile	49 km (3%)	4 km (0.2%)
>75th %ile	201 km (12%)	7 km (0.4%)
>50th %ile	473 km (27%)	15 km (0.9%)

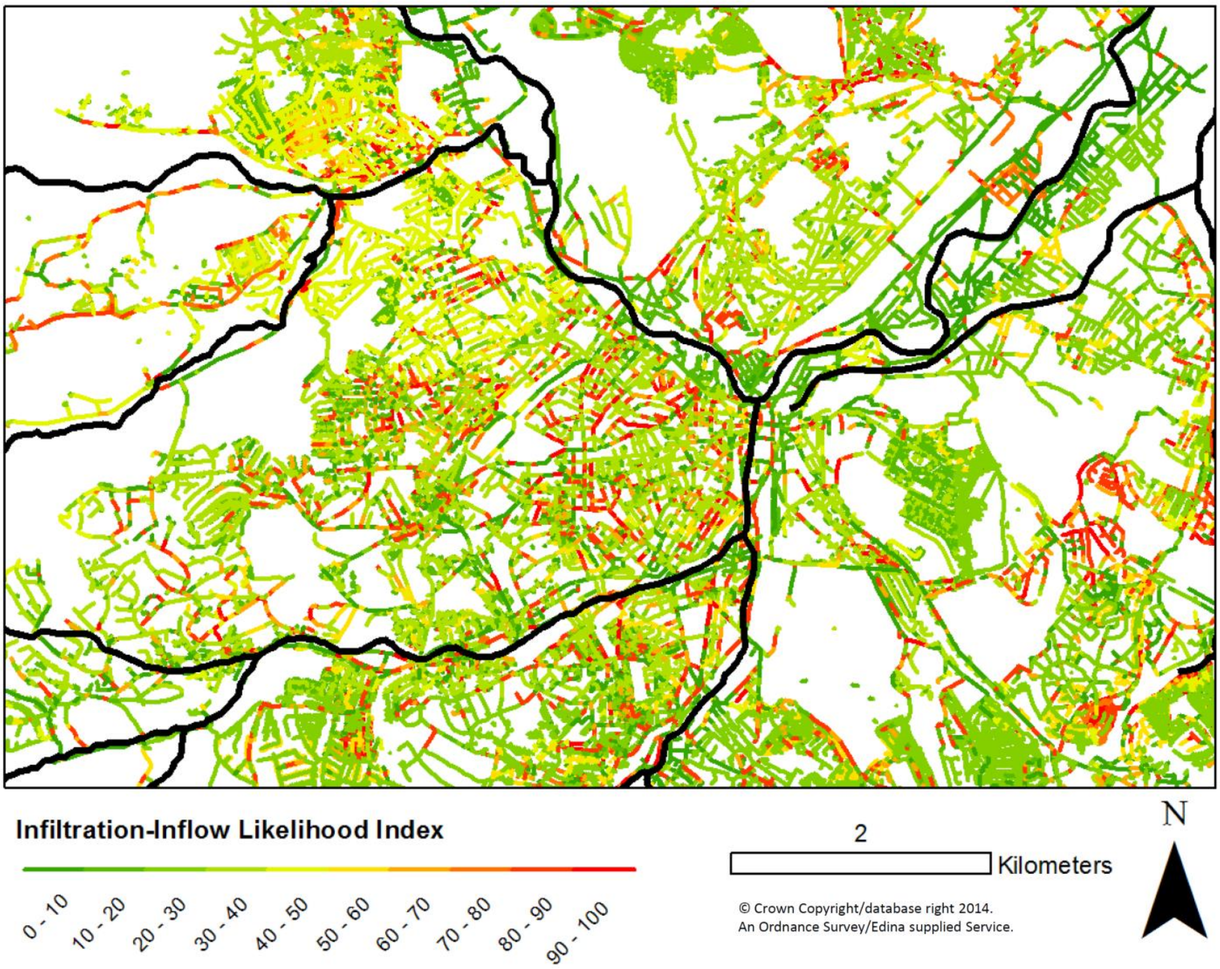


Figure 35 Sheffield combined sewer network colour-coded by infiltration-inflow likelihood index. The river and canal network are outlined in black for reference.

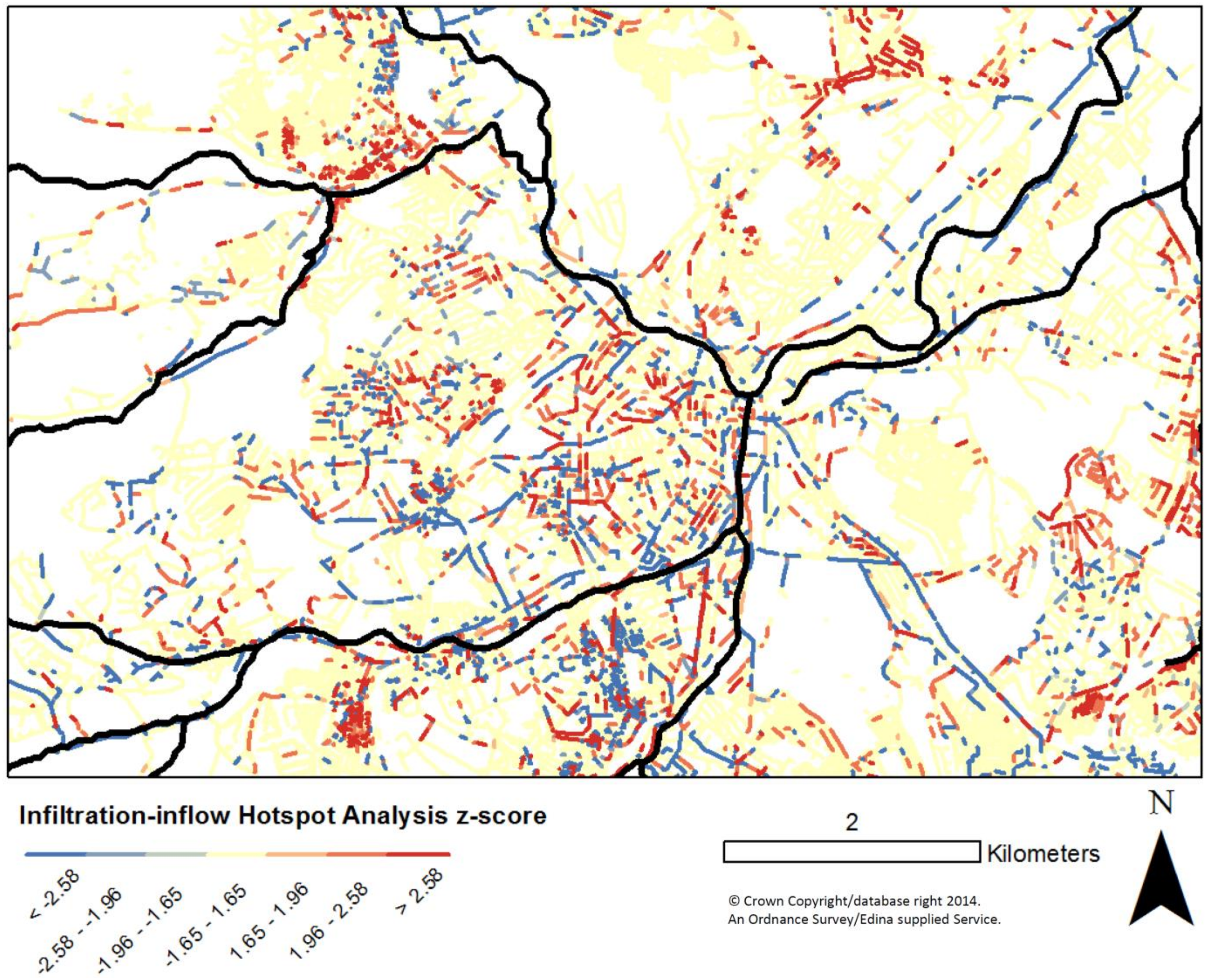


Figure 36 Sheffield combined sewer network colour-coded by Getis-Ord Gi* z-score of modelled infiltration-inflow likelihood index, showing hotspots of high infiltration-inflow likelihood (red). The river and canal network are outlined in black for reference.

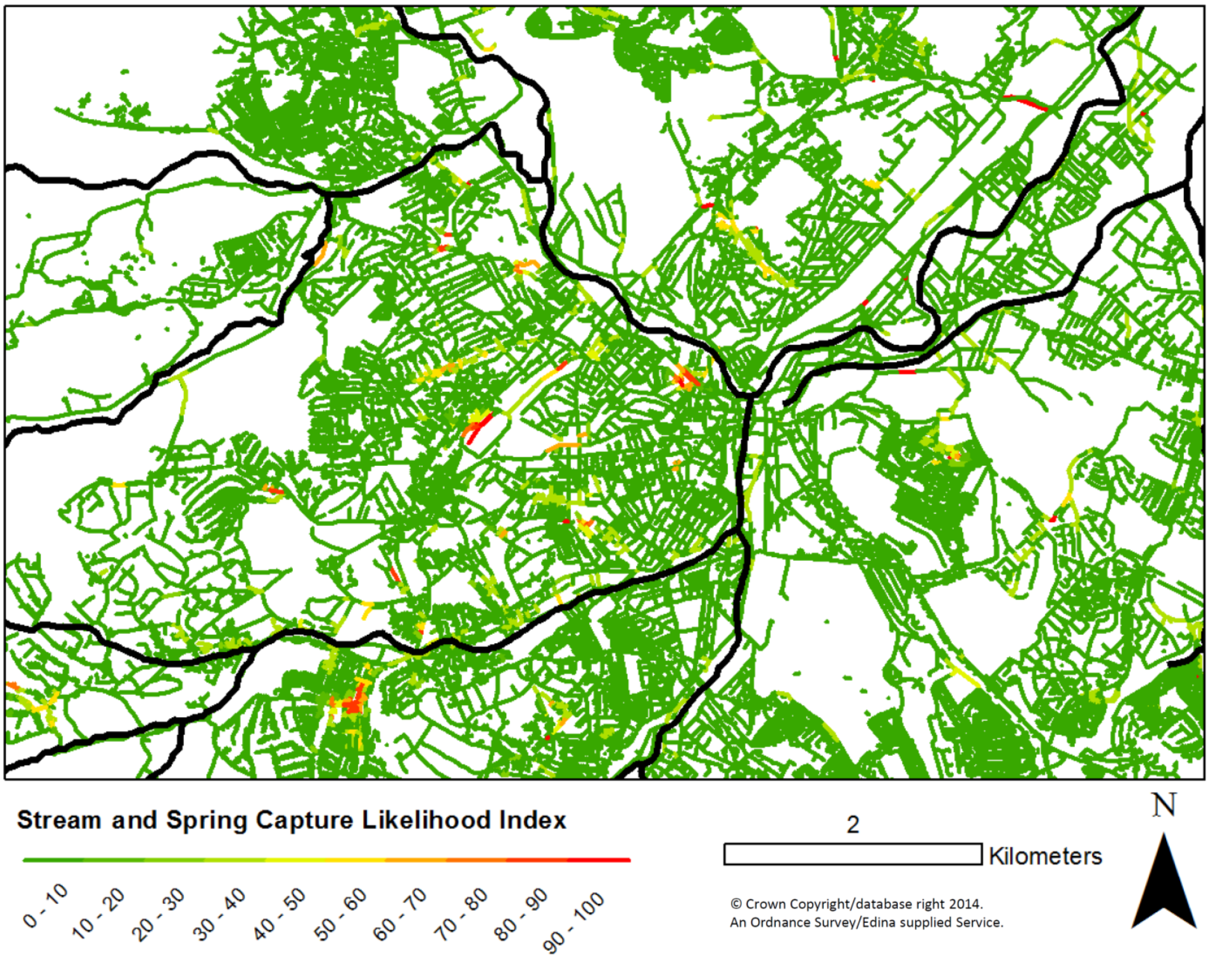


Figure 37 Sheffield combined sewer network colour-coded by stream and spring capture likelihood index. The river and canal network are outlined in black for reference.

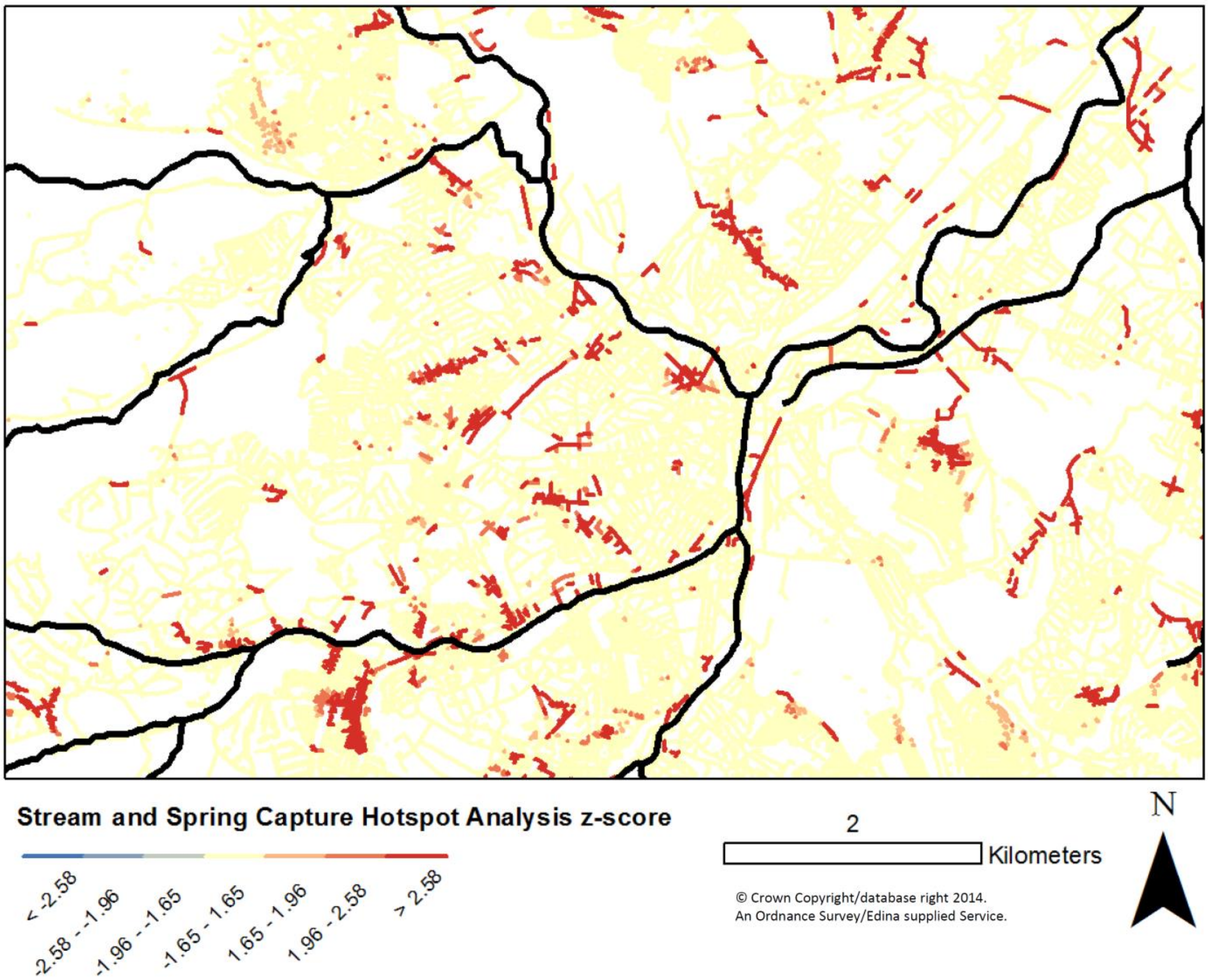


Figure 38 Sheffield combined sewer network colour-coded by Getis-Ord Gi* z-score of modelled stream and spring capture likelihood index, showing hotspots of high capture likelihood (red). The river and canal network are outlined in black for reference.

5.4 *Model evaluation*

The lack of plentiful data on infiltration-inflow and on stream and spring capture influenced the decision to use a Bayesian modelling approach rather than an empirical data-driven modelling approach. However, this also poses a challenge for model validation, especially for stream and spring capture, because there has not been any substantial data collection by the water industry on this recently identified issue. A multi-stage validation and sensitivity analysis process was conducted to test the model against the best available data.

5.4.1 Model sensitivity

Model sensitivity refers to how much a model variable is explained by other variables (Marcot 2012). For this, mutual information (*I*), the expected reduction in uncertainty of a variable *Q* given findings at another variable *F*, was calculated in Netica as:

$$I = \mathrm{H(Q)} - \mathrm{H(Q|F)} = \sum_{q} f \frac{\mathrm{P}(q.f)\log_2\left(\mathrm{P}(q.f)\right)}{\mathrm{P}(q)\mathrm{P}(f)}$$

where H(Q) is the entropy (uncertainty) of Q before any findings; H(Q|F) is the entropy (uncertainty) of Q given findings at F; *q* is a given state of variable Q; *f* is a given state of variable F; and where *I* is measured in information bits (Marcot 2012).

Mutual information values reported in **Table 18** and **Table 19** show that *Capture By Interception*, as predicted relatively simply by *GIS-mapped Watercourse Inflows*, has the greatest influence on overall likelihood of *Capture Presence*, followed by *Capture By Conversion* then *Direct Spring Capture*. *Topographic Flowpath Lines* have a greater influence than *Street / Place Names* or even *Old Maps* on predicting the likelihood of *Presence of a Lost Watercourse*.

The results show a low sensitivity of the *Infiltration-inflow Presence* variable and the *Capture Presence* variable to the other variables. *Sewer Condition (Leakiness)* has a greater influence on *Infiltration-inflow Presence* than the *Lateral Pipe Condition* and *Water Availability At The Sewer*. The most important variable influencing the sewer condition is the *Observed Sewer Condition*, which is derived from CCTV surveys via the *MSCC Structural Condition Grade* variable in a small minority of cases. After this, the *External Stressor Factors* were generally more important than the *Sewer Fabric Factors* in influencing the *Predicted*

Sewer Condition. *Groundwater Availability* has a greater influence on infiltration-inflow than the *Soilwater* or *Mains Leakage Availability*.

Table 18 Sensitivity of *Infiltration-inflow Presence* node to findings at other variables, ordered by importance. Colours denote variable groups: red – sewer condition group; blue – water availability group; green – lateral sewer group. Strength of shading differentiates the order of variable levels in the model, with the lightest being the first input nodes and darkest being the parent nodes to the Infiltration-inflow presence variable.

Infiltration-inflow presence	**Mutual Information (*I*)**
Sewer Condition	0.01929
Lateral Pipe Condition	0.01856
Water Availability At Sewer	0.01595
Observed Sewer Condition	0.00837
MSCC Structural Survey Score	0.00338
Lateral Pipe Age	0.00119
Groundwater Availability	0.00105
Predicted Sewer Condition	0.00049
Groundwater Approximate Relative Depth	0.00045
Soilwater Availability	0.00034
Mains Leakage Availability	0.00016
External Stressors	0.00004
Soil Permeability	0.00003
Proximity Sewer to Mains	0.00002
Sewer Fabric	0.00002
Ground Stability	0.00000
Pipe Lining	0.00000
Road Type	0.00000
Material	0.00000
Age	0.00000
Size	0.00000

Table 19 Sensitivity of *Capture Presence* node to findings at other variables, ordered by importance. Colours denote variable groups: green – capture by interception group; red – capture by conversion group; blue – direct spring capture group. Strength of shading differentiates the order of variable levels in the model, with the lightest being the first input nodes and darkest being the parent nodes to the Infiltration-inflow presence variable.

Stream and spring capture presence	**Mutual Information (*I*)**
Capture By Interception	0.06138
Capture By Conversion	0.04895
Direct Spring Capture	0.04696
Presence Of A Lost Watercourse	0.01558
GIS-mapped Watercourse Inflows	0.01283
Presence Of A Lost Spring	0.00836
Topographic Flowpath Modelling - watercourse	0.00068
Citizen Science - watercourse	0.00053
Old Maps - watercourse	0.00043
Other Information - watercourse	0.00040
Street / Place Names - springs	0.00035
Citizen Science - springs	0.00027
Street / Place Names - watercourse	0.00027
Old Maps - springs	0.00022
Other Information - springs	0.00021
Hydrogeological Springlines - springs	0.00014

Sensitivity does not imply accuracy in the model predictions, it only characterises the influence of the variables. It shows that the first input variables (those with no parents, which represent input values that can be measured, estimated or otherwise known) have a very weak influence on the final predicted presence of infiltration-inflow and stream and spring capture. The influence of the first input variables is diluted through the model to the final output variable of interest; with five node levels, the BBN reaches the limit advised in some literature (Chen and Pollino 2012). Given information for every first input variable about a particular sewer site, the predictive range of the output presence likelihood would be narrow.

The modelled range of probabilities for *Infiltration-inflow Presence* using the first input nodes is from 41.24% to 49.92%. This means that with all first input variables (*Material*, *Age*, *Soil Permeability* etc.) set to states expected to result in the most infiltration-inflow, the model predicts just under a fifty-fifty chance of infiltration-inflow, and the best case scenario still with over 40% chance of infiltration-inflow. In the 12.5% of sewers in the case study for which the MSCC data were available as a first input variable, the predicted range of probabilities for *Infiltration-inflow Presence* increases (36.86-55.16%) reflecting greater sensitivity and confidence in this variable. For *Capture Presence*, the range of probabilities is from 25.06% to 59.47% using the first input variables. The model therefore can predict down to a lower likelihood of capture than it can infiltration-inflow, and to a higher likelihood of capture than infiltration-inflow. Rather than the narrow range and relatively low probabilities implying the model can give precise probability predictions with low uncertainty, these results could be interpreted in one of three ways:

1. genuine expert belief in the low ability of the first input variables (such as *Sewer Material*, or *Street / Place Names*) to differentiate the highest and lowest likelihoods infiltration-inflow or stream and spring capture presence;
2. unintentional "centring" of probabilities arising from the process of aggregating expert questionnaire responses by averaging, which may not represent individual experts' genuine beliefs about the expected influence of the variables;
3. unintentional dilution of variable influence caused by the number of node levels, suggesting a weakness in the model structure.

There can be limited data availability for real life sewer networks, and the dataset used in this case study is typical, with many missing data for first input variables such as *Sewer Age*. For missing data, the BBN uses the underlying probability distribution, e.g. there could be a chance that the sewer is any age. The ability to handle missing data in this way is a key strength of a BBN, but it does reduce total predictive range of the model still further; for *Stream And Spring Capture Presence* the range of probabilities narrows from 25.06-59.47% to 25.75-42.31%. These narrow ranges of model outputs justify the ranking and indexing of probability values to differentiate the highest and lowest likelihoods of infiltration-inflow and stream and spring capture in the case study, rather than using the probabilities directly.

The flexibility of the BBN to update the probabilities in light of new knowledge means that the modeller is not restricted to using just the first input nodes. For example, site investigations could observe water in the sewer trench, enabling the intermediate variable *Water Availability At Sewer* be specified directly. This would bypass the modelled probabilities of *Water Availability At Sewer*, which were predicted from *Groundwater Availability*, *Soilwater Availability*, and *Mains Leakage Availability*, which in turn were predicted from *Approximate Relative Depth To Groundwater*, *Soil Permeability*, and *Proximity Of Sewer To Mains Pipe*. Using intermediate variables, which have greater influence on the final output variables, widens the predictive range of the model and thus more confidently differentiates sewers of higher and lower likelihoods of infiltration-inflow or capture. By using intermediate variables *MSCC Structural Condition Grade*, *Water Availability At Sewer* and *Lateral Pipe Condition*, the predictive range for *Infiltration-inflow Presence* increases from 36.86-55.16% to 23.53-75.10%. This differentiates sewers with a greater range of likelihoods, as well as increasing the maximum predicted likelihood of infiltration to a 75% chance of infiltration-inflow. By using intermediate variables *Capture By Conversion*, *Capture By Interception* and *Direct Spring Capture*, the predictive range for *Stream And Spring Capture Presence* increases from 25.06-59.47% to 10.00-93.80%. The model can predict from near certainty that capture is present to near certainty that it is not present, but this would require knowledge to be obtained to specify those intermediate variables. In reality, such knowledge may be simply unobtainable, and the values therefore can be interpreted as the experts' belief that there will be some remaining, unavoidable uncertainty about whether capture will be present even in the event that one of the capture types is stated to occur.

This raises the practical question of how the model could be used to incorporate new knowledge from site investigation or from the various lines of evidence to indicate capture outlined in Chapter 3, including results of tests such as the water typing developed in Chapter 4. A further expert workshop could be used to decide how the results of such tests could be incorporated by directly specifying the state of an existing variable with reasonable confidence. Alternatively, by targeting experts who have specific experience of using such tests and interpreting the results, the BBN structure could be modified to incorporate these tests as additional variables, weighted and parameterised with their expected performance accuracy.

5.4.2 Qualitative validation framework

Pitchforth and Mengersen (2013) drew on psychometric validation theory to suggest that BBN model validation should go beyond the typical focus on predictive accuracy and use qualitative feedback to test various wider aspects of the model's validity. The various types of validity were evaluated through qualitative and subjective assessment by the author and an independent expert, where possible. This structured assessment is summarised below.

Nomological validity establishes whether the BBN fits in context with the literature, identifying similar (nomologically adjacent) and dissimilar (nomologically distant) themes and ideas. This BBN does fit into the context of the literature: predicting the likelihood of infiltration-inflow has been undertaken before (UKWIR 2012) and consideration of how infiltration-inflow is influenced by sewer condition is also widely covered (Arthur and Burkhard 2010, Chughtai and Zayed 2008, Egger et al. 2013, Fenner and Sweeting 1999, Harris and Dobson 2006, Rieckermann et al. 2010, Shehab and Moselhi 2005, Wright et al. 2006, Zhang 2005). Stream and spring capture is a relatively new concept in these terms, and though it is supported by literature (Chapter 2), it purposely sits on the edge of the current knowledge.

Face validity assesses whether the model structure and node discretisation look the same as experts or literature predict. The two expert workshops arrived independently at similar model structures and chosen variables. This was also similar, but with a greater number of variables, to the model attempted previously (UKWIR 2012). The node discretisation was discussed by experts in the workshop. Some changes were made by the author to simplify or match discretisation to available data; though this was not discussed in detail with the experts, no feedback from the questionnaires identified this as an issue. Many nodes were discretised into simple relative states (e.g. high, medium or low), and this subjectivity was perceived by the experts to be within the bounds of their ability to give estimates on a relative basis.

Content validity establishes whether the model includes all and only model variables relevant to the model output, whether each node includes all and only the relevant states, and whether node states are dimensionally consistent. In this BBN, some variables identified in the expert workshops were excluded for simplicity, especially where they were considered to be relevant only in specific situations such as sewer corrosion issues or tidal groundwater influence. Some experts noted that variables reflecting observed data were not included directly in the model, such as the use of chemistry-based or sewer flow hydrograph techniques to indicate and quantify infiltration-inflow. These were purposely excluded by the author because such data would likely be available only on a site-by-site basis rather than at a network scale; they can however be incorporated implicitly into the model to specify the state of intermediate variables following further investigation. Each node can have states that are plausible and experts did not identify any missing states. For ease of integration with Netica, some continuous states are limited at the extremes – for example, sewer age begins with 1800 to 1919, but the input data can easily be modified such that sewers constructed prior to 1800 are not excluded.

Concurrent validity tests whether the BBN structure or sub-networks are discretised, parameterised and behave similarly to ones modelling theoretically related problems. In this BBN, sub-networks predicting the presence of a lost watercourse or the presence of a lost spring are predicted from similar first input variables, which are worded consistently, but specify the different focus accordingly. The sub-network to predict capture by interception is different, however, reflecting the different processes perceived to be involved and instead this is predicted directly from GIS-mapped watercourse inflows. For the infiltration-inflow sub-network, the condition of the lateral pipes is not predicted in the same way as for the condition of the sewers, rather only from lateral pipe age. The discretisation of the lateral pipe age was chosen to mirror the sewer age variable because this best reflected available data, but the overall simplification was chosen because of a considerable lack of any widespread data collection on lateral pipes. A key comparison in this BBN is the similarity between the infiltration-inflow and the stream and spring capture sub-networks. The predictions for infiltration-inflow reflect the working definition of unintentional leakage through pipe cracks and defective joints, and the model therefore attempts to predict the presence of such defects and the presence of water. The approach for stream and spring capture is quite different, focusing less on water availability and instead on proximity of a sewer to watercourses or springs. Theoretically, there could even be overlap between infiltration-inflow and capture: infiltration-inflow may occur in sewers that had been converted from an old watercourse because there may be no discrete inflow point, and direct spring capture may occur through land drains and enter sewers as infiltration-inflow through the lateral pipes. These issues do not necessarily imply a poor concurrent validity because they were purposely chosen to enable a comparison between infiltration-inflow and stream and spring capture, but future development may wish to consider better integrating them with regard to the underlying hydrological processes.

Convergent validity assesses how similar the model structure, variable discretisation and parameterisation is to other models that are nomologically adjacent. A suitable comparison for this BBN is the model attempted previously by UKWIR (2012). In that model, infiltration-inflow was discretised as a nominal scale from 1-10, whereas this BBN simplified this as a likelihood of being either present or not present. This was purposely done so that the model output could directly plot the likelihood of infiltration-inflow for each sewer, and not have to aggregate a probability distribution across a dimensionless 1-10 scale into a single value for plotting. Further simplifications were made in this study, such as excluding pipe shape as a predictor of sewer condition, and in the reduction in the number of possible states for variables such as *Sewer Age* and *Water Availability At Sewer*. There are no known comparative models against which to test the convergent validity of the stream and spring capture sub-network; the UKWIR study may have implicitly included this within its prediction of infiltration-inflow, but this was not explicitly defined.

Discriminant validity assesses how similar the model structure, variable discretisation and parameterisation are to other models that are nomologically distant. Of the suggested tests in the framework by Pitchforth and Mengersen (2013), this is the most difficult to answer because there are no appropriate models from the literature against which to test. The suggested question, "when presented by a range of plausible models, can experts choose the 'correct' model?" (Pitchforth and Mengersen 2013: 166) is appropriate, however. Further development could usefully present several similar model structures to a wider range of experts that were not involved in this model development (thus independent). The degree to which they can discriminate the correct model could measure the confidence in the model structure itself, and outputs from other plausible model structures could measure the importance of this on the overall model accuracy.

5.4.3 Validation of infiltration-inflow presence predictions

Available data have been used to test the predictive validity of the model. The infiltration-inflow sub-network predicts the likelihood that infiltration-inflow is entering the sewer through pipe cracks and joints. For the entire network of 99,902 segments of combined sewer, 12,592 have been surveyed by CCTV. Of these, 273 observed and recorded infiltration-inflow. Surveys were conducted using the MSCC procedures and receive quality assurance checks by Yorkshire Water (Richard Kidd, Yorkshire Water, pers. comm. 28th March 2014). While it is possible that repeat surveys during different seasons may result in infiltration-inflow being observed where not recorded before or vice versa, this provides the best available evidence for use at present.

The predicted probabilities of infiltration-inflow being present are significantly higher at sites where infiltration-inflow has been observed (mean 44.5%; $\sigma=0.037$; $n=273$) than at sites where it has not been observed (mean 43.3%; $\sigma=0.038$; $n=12319$); tested with a two-sample t-test with $p<0.000001$. Despite the relatively small difference in the values of the predicted likelihoods, the ability of the model to differentiate between higher and lower likelihoods appears to be very good, given the available data. This further supports the use of the model output as a relative index rather than absolute probability of infiltration-inflow or stream and spring capture.

5.4.4 Validation of stream and spring capture presence predictions

In lieu of extensive validation data for sites of stream and spring capture, the first stage of validation consisted of testing the model results at eight specific sites with which the author has some familiarity from previous site investigation and a good level of understanding of what is happening at each. The model correctly predicted higher capture presence probabilities in four sites where capture by interception, capture by conversion and direct spring capture are known to occur, and illustrated in detail for one site in **Figure 39**. It correctly predicted low capture likelihoods at three sites where, from a detailed review of evidence and site visits, the author strongly believes there to be no capture occurring. The eighth site was incorrectly predicted as being a low capture likelihood, despite a culverted watercourse (now a surface water sewer) probably flowing directly into a combined sewer. This was not picked up by the model due to the input data not identifying this GIS-mapped watercourse inflow – the surface water sewer is shown to end approximately 10 m away in a nearby park, but no outfall can be seen on site. It is therefore assumed that the sewer network data were imprecisely located, and that the surface water sewer probably does discharge into the combined sewer. Given the sensitivity of the model to this unexpected data imprecision, further development could use expert knowledge to assign an appropriate proximity threshold for the *GIS-mapped Watercourse Inflow* variable.

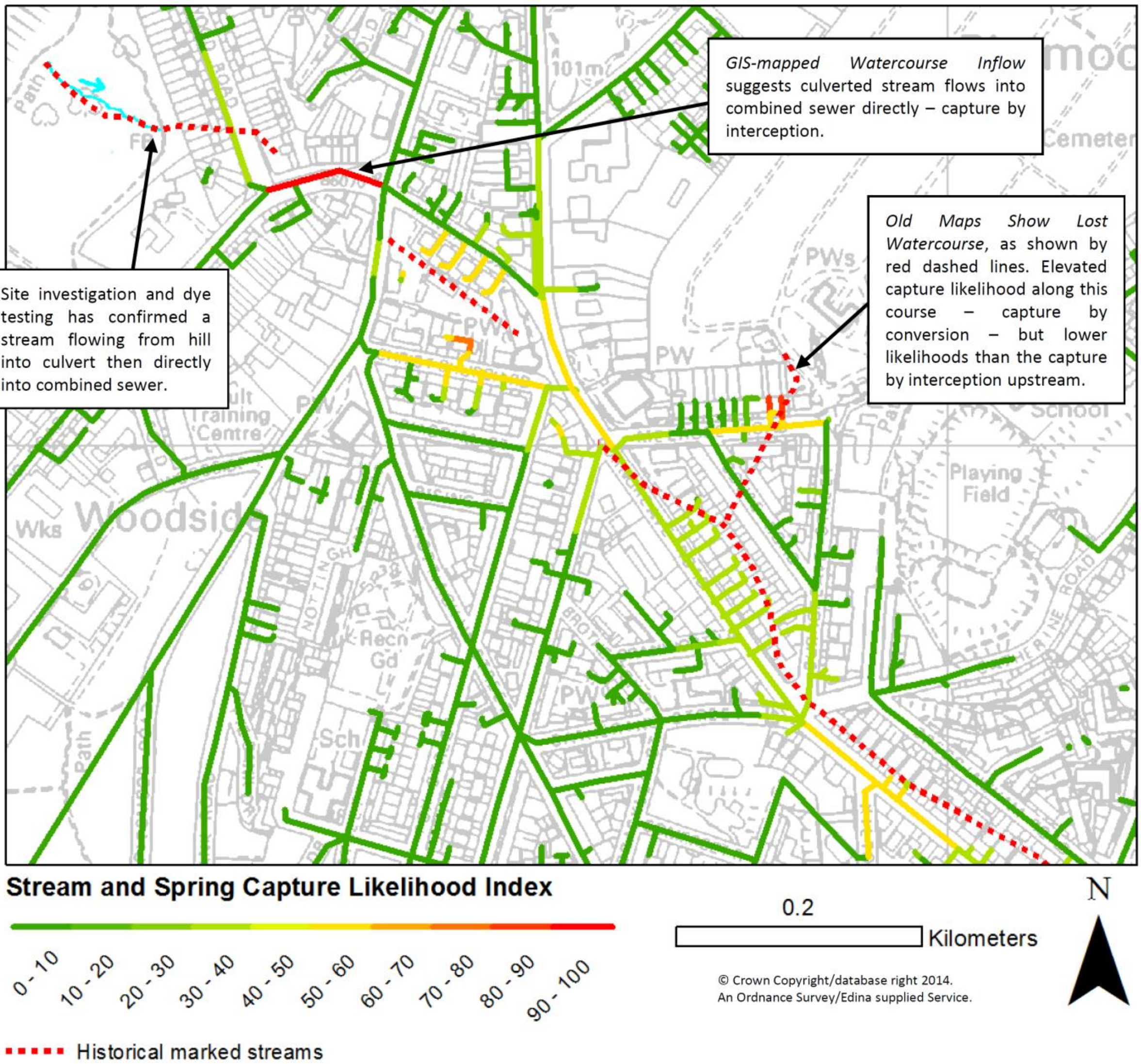


Figure 39 Correctly predicted stream and spring capture at one site, where a watercourse is known to flow into a combined sewer. Combined sewers are colour coded by the Stream and Spring Capture Likelihood Index, which also picks up elevated capture likelihood along the route of an historic stream shown on old maps (dashed red).

Table 20 Confusion Matrix for results of the question "would further investigation of this specific sewer be recommended to confirm or rule out capture?"

Specific sewer		**Observed** sites	
		Capture	No Capture
BBN Model **Prediction**	Capture	9 (TP)	21 (FP)
	No Capture	0 (FN)	30 (TN)

Table 21 Confusion Matrix for results of the question "would further investigation of sewers in this immediate area be recommended to confirm of rule out capture?"

Sewers in immediate area		**Observed** sites	
		Capture	No Capture
BBN Model **Prediction**	Capture	26 (TP)	4 (FP)
	No Capture	0 (FN)	30 (TN)

The second stage of validation was to take a random sample of 30 sewer segments from the 1% of combined sewers with the highest predicted likelihood of capture presence and 30 from the 1% of combined sewers with the lowest predicted likelihood of capture presence. Using judgement by the author and further review of data such as sewer network maps, old maps or historical texts, these 60 sampled sites were evaluated by asking "would further investigation of this specific sewer be recommended to confirm or rule out capture?" and "would further investigation of sewers in this immediate area be recommended to confirm or rule out capture?". For the purpose of this analysis, the definition of "in this immediate area" typically included sewers within 100 m but was visually judged based on the local topography. An answer of "yes" means capture is present and an answer of "no" means no capture is present. These are assumed to be true observations in this context, representing the anticipated use of the model by the water industry to target further investigation or tests on individual sewers or at least areas of the sewer network. Results were classified as true positive (TP), false positive (FP), true negative (TN) or false negative (FN), and the classification results are given in Confusion Matrices (**Table 20** and **Table 21**).

Various metrics of model predictive performance are possible using these scores, and some are summarised in **Table 22**. Of particular note is that the fraction of Correctly Classified Instances (accuracy) of the model increases from 0.65 to 0.93 if the results of sewers in the immediate area are considered. This suggests a very strong model performance is possible to target an area of sewers for further investigation. Experts may even consider the lower 0.65 value as a reasonable predictive performance to target individual sewers, which could be further explored with additional expert knowledge elicitation; as suggested by Marcot (2012: 51): "in decision analysis, the risk attitude of the decision-maker determines the degree of error they might accept". Part of this high accuracy is accounted for by the perfect True Positive Rate, i.e. there were no false negatives in this sample despite one false negative being identified and discussed previously. If the model were to be used as a scoping tool to identify sewers for further investigation, false negatives are logically less desirable than false positives, because many false positives can be quickly discounted and ruled out by looking at the sewer network maps. Even so, the false positive rate is not overly high.

Table 22 Metrics used with a Confusion Matrix, with meanings in the context of this study (Agresti 1990, Fawcett 2006, Fielding and Bell 1997).

Measure	**Formula**	**Meaning**	**Specific sewer**	**Sewers in area**
Correctly Classified Instances (accuracy)	$\frac{(\mathrm{TP}+\mathrm{TN})}{N}$	Overall fraction of sample sites that were correctly predicted.	0.65	0.93
True Positive Rate (sensitivity, recall or hit rate)	$\frac{\mathrm{TP}}{(\mathrm{TP}+\mathrm{FN})}$	Fraction of truly captured sample sites that were correctly predicted as captured. This should ideally be high.	1.00	1.00
False Positive Rate (fallout, false alarm rate)	$\frac{\mathrm{FP}}{(\mathrm{FP}+\mathrm{TN})}$	Fraction of truly not captured sample sites that were incorrectly predicted as captured.	0.41	0.12
Positive Predictive Power (precision)	$\frac{\mathrm{TP}}{(\mathrm{TP}+\mathrm{FP})}$	Fraction of sample sites predicted as captured that are truly captured.	0.30	0.87

Cohen's kappa (K) was chosen as a key performance indicator because it combines all of the error types (Fielding and Bell 1997). It is a measure between $-\infty$ and 1 of the agreement taking into account the agreement expected to occur by chance:

$$K = \frac{(\mathrm{TP}+\mathrm{TN}) - \left(\frac{\left((\mathrm{TP}+\mathrm{TN})\cdot(\mathrm{TP}+\mathrm{FP}) + (\mathrm{FP}+\mathrm{TN})\cdot(\mathrm{FN}+\mathrm{TN})\right)}{N}\right)}{N - \left(\frac{\left((\mathrm{TP}+\mathrm{FN})\cdot(\mathrm{TP}+\mathrm{FP}) + (\mathrm{FP}+\mathrm{TN})\cdot(\mathrm{FN}+\mathrm{TN})\right)}{N}\right)}$$

Where N is the number of samples; $K<0$ being an agreement less than that expected by chance; $K=0$ being the agreement expected by chance; $K=1$ being a perfect classification agreement.

K is 0.30 when considering the result only at the specific sewer, but rises to 0.87 when considering the surrounding sewers. Interpretation of K scores usually follows the widely cited benchmark descriptions suggested by Landis and Koch (1977), though this was a suggested interpretation that they did not fully justify (**Table 23**). The subjectivity of this interpretation means that the scores are best considered in relative terms rather than in terms of absolute agreement. This could enable comparison of this BBN against further revisions by users in the water industry.

Table 23 Evaluation thresholds for Cohen's kappa K (Landis and Koch 1977).

K	**Strength of agreement**
<0.00	Poor
0.00 – 0.2	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 1.00	Almost perfect

This supports the model's fitness-for-purpose for scoping areas of sewer networks with elevated likelihood of stream and spring capture in order to recommend further investigation to confirm or rule it out. The model should therefore be conservative and slightly over-predictive: false positives are more desirable than false negatives, as is the case. The model may not always pin-point the precise sewer where capture is occurring, but further review of the results in zones of higher risk should be sufficient to target efforts to certain sewers.

5.5 Conclusions

This study has successfully developed a BBN tool to predict stream and spring capture and infiltration-inflow to combined sewer systems. The BBN modelling approach has utilised and quantified expert knowledge to predict stream and spring capture and infiltration-inflow likelihoods for Sheffield. The model correctly predicts higher probabilities of infiltration-inflow in sewers that have been observed to have infiltration-inflow from CCTV. Stream and spring capture is more difficult to validate, but tests have shown that it performs well, correctly identifying the few known capture sites, and positively identifying numerous sites that, on review, would be worth further on-site investigation to confirm or rule out capture.

The model development suggested that experts were in broad agreement over the many variables that influence the presence of infiltration-inflow and stream and spring capture. There was generally a lower confidence in the expert responses to the predict capture, reflecting this being a relatively new concept. Given the promising results from just five expert knowledge elicitation questionnaires, there is now opportunity for the water industry to apply the model and refine the results with further experts from both the UK and internationally.

Model application to the case study catchment has shown that predicted stream and spring capture is more spatially localised than infiltration-inflow. This reflects the experts' beliefs and the model design. Consequently, the model suggests that stream and spring capture affects a much smaller proportion of the network than infiltration-inflow. It should not be inferred that this means stream and spring capture contributes less water to the combined sewer system; particularly on a local scale, stream and spring capture could be contributing substantial amounts of clean water into an otherwise watertight sewer that is unlikely to be vulnerable to infiltration-inflow. On this basis, stream and spring capture is worthy of further attention by the water industry.

The BBN model presented would make a useful scoping tool for water companies to assess the likely areas of capture and infiltration-inflow risk in their sewer networks. One of the key advantages is that the BBN approach can compile evidence from multiple sources of information, and be updated in light of new information for further on-site investigation – either implicitly within this model, or explicitly by incorporating new variables.

6 Thesis Conclusion

6.1 Introduction

The aim of this thesis was to demonstrate that streams and springs have been captured into the combined sewer system, and to develop methods to identify where this occurs. This chapter draws together the findings of the thesis chapters to address the objectives and the overall aim. It will also explore the wider implications of this work and make recommendations for the water industry, particularly considering the management opportunities and barriers to change in the UK context. Finally, it will outline some key future research questions that this study has raised.

6.2 Synthesis of research findings

6.2.1 Establish existing state of knowledge on stream and spring capture

Chapter 2 presented the first dedicated review of the evidence on stream and spring capture, drawing on both the peer-reviewed academic literature and grey literature. Numerous examples were found from around the world where streams and springs have been reportedly captured into combined sewer systems. The review demonstrated that the literature is often unclear as to whether the watercourses have become culverted surface water sewers and continue to flow to river networks, or whether they do now flow in combined sewers to the WwTW. This reflects the fact that stream and spring capture has rarely been explicitly considered with regard to the impacts on the combined sewer system itself. Furthermore, no studies provide a clear methodology to indicate where lost streams and springs may be captured into the combined sewer system, supporting the thesis objectives to explore this for the first time.

Stream and spring capture was deduced from the literature to occur in three main ways, and the following definitions have been used throughout the thesis:

1. capture by conversion is the intentional historical replacement of a watercourse by a combined sewer, capturing the clean spring-fed baseflow at source, with no known discrete inflow;

2. capture by interception is the intentional discrete inflow of an open or culverted watercourse into an intercepting combined sewer;
3. direct spring capture is the intentional drainage of shallow groundwater or springs piped into a combined sewer, and a discrete inflow point to the sewer may be difficult to identify.

Stream and spring capture is therefore an intentional inflow of clean baseflow to the combined sewer, often associated with the historical development of the sewer system. This contrasts with infiltration-inflow, which is the unintentional ingress of groundwater baseflow into the combined sewer, typically through pipe cracks and defective joints, and which may be seasonally varying. However, once in the combined sewer, the literature suggests that the effects of captured water may be similar to infiltration-inflow; principally, higher capital and operational costs associated with increased baseflow to WwTWs. Infiltration-inflow has been, and continues to be, widely covered in the academic literature with methods to predict, detect and quantify it, and this reflects interest in the water industry to reduce infiltration-inflow. Definitions of infiltration-inflow do not adequately consider the intentional connection of streams and springs to combined sewers, and this ought to now be amended to reflect another source of clean baseflow to combined sewer systems.

Stream and spring capture also represents wider environmental, social and economic costs associated with the loss of urban watercourses. Just one detailed study (Zurich, Switzerland) has explicitly considered the impact of stream and spring capture, and has taken steps over the last few decades to separate the clean baseflow from the combined sewer system to reduce wastewater treatment costs and urban flooding through the daylighting and restoration of the lost watercourses as natural surface water features. The Zurich case study details neither a useable methodology nor independent evaluation of the results, but provides a highly promising exemplar to the water industry around the world to consider this issue.

The literature review presents a strong case that stream and spring capture occurs, that similar to infiltration-inflow it can have considerable capital and operational costs for the water industry, and that a methodology is needed to indicate where it occurs. Developing a methodology to indicate capture would enable water companies to fully assess their combined sewer networks for this additional source of clean baseflow, and is an essential first step before the costs, opportunities and benefits of managing it can be evaluated.

6.2.2 Develop and apply a method to indicate where capture occurs

Chapter 3 outlined and applied a methodology to indicate where streams and spring have been captured into combined sewer systems. While studies have previously been undertaken to identify stream burial, this is the first critical review of evidence available specifically to indicate where lost streams and springs may not only have been culverted but captured into the combined sewer system. The presentation of the methodology as a flowchart, which summarises the key steps and lines of evidence, is the main outcome of this chapter.

The first stage of the method is to locate lost streams and springs. The second stage is to indicate where the lost streams appear to have been intercepted by or converted into combined sewers and where lost springs may have been directly captured into nearby combined sewers. The third stage is to verify, where possible, using on-site investigations to confirm connectivity. There are multiple lines of evidence available for each of these three stages, which were reviewed from the literature, applied to the case study catchment, and then qualitatively assessed for the criteria of data availability, time and resource requirements, and potential reliability. Desk-based evidence that can be used to locate lost streams and springs includes modern maps, historical maps, street and place names, information derived from the public (citizen science), and information derived from historical written accounts or paintings. Previous studies mapping stream burial have usually considered only topographic flowpath lines modelled from digital elevation models (DEMs) using GIS. This technique was found to offer a quick and reasonably reliable means of identifying likely stream locations, but application to the case study catchment demonstrated that it does not accurately locate all streams seen on historical maps. Historical maps, though widely available, often require time-consuming manual searches over entire catchments at a range of map scales and ages, and their interpretation is not always straightforward. Other evidence, such as street and place names or from the public, can offer important corroboration in many cases, and should not be underestimated.

Identifying the limitations and uncertainties associated with each line of evidence is a key outcome of this study, leading to the recommendation that all are combined to improve confidence. As reflected in the flowchart, it is recommended that topographic flowpath modelling is used as an initial screening to help target more time-consuming desk-based searches of evidence. Overall, the location of lost streams and springs using this evidence is an essential step to enable efficient targeting of any steps to indicate where they may be captured into combined sewers.

Options to indicate capture include desk-based comparisons of the predicted locations of lost streams and springs with sewer network maps, as well as more involved methods that can require further data collection, such as from sewer network hydraulic models, water balance calculations, or water chemistry based techniques. Each of these involve limitations also: sewer network maps can be incorrect or incomplete; assessing capture from flow hydrographs or water balance is an indirect indication and may not easily differentiate capture from infiltration-inflow or other clean baseflow in the sewer. In cases where a direct inflow cannot not be found, such as for capture by conversion or direct spring capture, the lines of evidence above may offer the best available evidence to confirm or verify capture. Application of multiple lines of evidence is therefore recommended to offer a weight of evidence. In cases of capture by interception, where a direct inflow can be found, it is possible to verify that capture is occurring through visual inspection or connectivity testing, which is a direct confirmation.

Application of the methodology to a case study catchment demonstrated that while 22% of the known stream and river network length is culverted, there are many small lost streams and springs that have disappeared beneath the urban area of Sheffield. When these are taken into account, a little over half of the total stream length may have been lost. Lost streams may be flowing in unmapped culverts, or in surface water sewers and eventually discharge to the river network, or they may be captured into the combined sewer system. In addition, over 100 springs appear to have been lost from the urban area. Several cases that were indicated to be captured were confirmed by site investigation, demonstrating that capture is highly likely to be occurring in this case study catchment. The water industry should now apply and refine the methodology outlined in this chapter to new sewer catchments.

6.2.3 Develop and apply a water typing method to detect capture

Chapter 4 demonstrated the first known application of a water typing method to detecting stream and spring capture. A number of water chemistry-based techniques have previously been developed and applied to detecting infiltration-inflow in combined sewers, but they may present some uncertainty when applied to the detection of captured streams and springs. It is unlikely for there to be a single unique chemical marker present only in captured waters and not in wastewater, and while other studies have demonstrated the use of chemical oxygen demand (COD), total suspended solids (TSS) or stable isotopes in combination with sewer flow hydrographs, they require an assumption of the baseline chemistry such as 0 mg/L COD in captured waters. The use of major ion water typing has been widely applied in a range of hydrogeology studies for many years to characterise and detect mixing between groups of surface or groundwaters. It has not previously been applied to detecting either captured streams and springs or infiltration-inflow in combined sewer systems, and yet major ions are present in all waters, are relatively conservative, and are easily analysed, looking not for presence or absence but the relative proportions. They may be applicable wherever tapwaters (the major constituent of wastewater) are imported from an area of different geology and are of a different chemical water type to local groundwaters supplying lost streams and springs. This could detect the mixing between captured waters and wastewater in combined sewers to indicate capture, potentially offering an alternative technique to complement existing approaches to detect infiltration-inflow.

Using the methodology outlined in Chapter 3, four sites of capture by interception, capture by conversion and direct spring capture were chosen. A fifth site was chosen at which no capture was expected. At each site, samples were taken from the combined sewers upstream and downstream of expected capture and from the watercourse inflow, wherever possible. Multiple spot samples were taken within a 15-30 minute period, for 3-5 days, during both the night-time minimum (where wastewater inputs are lowest and thus capture is proportionally highest) and the daily peak flow (where wastewater inputs are highest and capture is proportionally lowest). Samples from tapwaters and from springs from different geologies in and around the city were also taken. Samples were analysed for major ions, minor ions and metals, and COD (for comparison to COD pollutant hydrograph methods used for infiltration-inflow). Despite high frequency variations in chemistry, major ion and minor ion wastewater chemistry types were actually relatively consistent. COD of wastewater varied diurnally as expected, but was often present in captured waters; the assumption of 0 mg/L COD as used in pollutant-hydrograph approaches may not be suitable in all cases or for captured streams and springs, which may have been polluted.

At sites where a discrete captured inflow was found to the combined sewer and where this could be accessed for sampling, major ion water typing clearly showed the clean captured water mixing in the sewer. In two cases, it was even possible to use a mixing line between the two end-point water types to approximately quantify the proportion of captured water in the combined sewer. In one of these, the flow in the combined sewer consisted of 60-90% captured water during the daytime – a substantial proportion. Minor ions corroborated these findings.

In the study catchment, spatially complex geology gives rise to spatially varied groundwater chemistry. This makes it difficult to predict the water type of captured waters, or indeed infiltration-inflow, and thus the method requires the end-points to be accessed for sampling. It is therefore most suited to detecting capture by interception; capture by conversion or direct spring capture may not present a clearly identifiable discrete inflow to sample. However, in catchments where the geology and groundwater chemistry is less complex and can be predicted, the water typing method may be applicable for all types of capture.

6.2.4 Develop and apply a predictive model to compare capture and infiltration-inflow

Chapter 5 developed and applied an expert knowledge Bayesian Belief Network (BBN) model to predict the likelihood of stream and spring capture and infiltration-inflow to combined sewers. Chapter 3 identified multiple lines of evidence to locate lost streams and springs and indicate where capture occurs, and this model integrates the simple desk-based evidence into a framework suitable for scoping an entire sewer catchment for the most likely sewers or areas of sewer to target further, more expensive tests to indicate or confirm capture.

The BBN substantially builds on previous work by UKWIR (2012) that attempted to predict the risk of infiltration-inflow to sewers. However, it was built from the ground-up, eliciting a new model structure from a new group of experts, and therefore includes some important modifications and improvements over the previous model structure. In particular, it explicitly separates stream and spring capture and infiltration-inflow based on the different causes and entry mechanisms to the sewer, and predicts simply the likelihoods of them being present or absent. This approach was considered suitable for the purpose of differentiating sewers with the highest likelihoods of stream and spring capture or infiltration-inflow, in order to target these sewers for further site investigation or tests.

This BBN also underwent a thorough multi-stage validation exercise that was not possible for the previous model. This showed that the model predicted significantly higher infiltration-inflow likelihood at sites where infiltration-inflow has been observed, using CCTV survey data from the water company. For stream and spring capture, the model successfully predicted elevated capture likelihood in most cases where capture was already known and confirmed from previous chapters, and was able to reliably differentiate areas of the sewer network where further investigation to confirm capture would be desirable.

The study also showed that stream and spring capture is likely to be occurring in sewers not likely to be experiencing infiltration-inflow. Because it reflects the locations of lost streams and springs, capture is also more spatially clustered than infiltration-inflow.

BBNs and expert knowledge models have been increasingly finding applications in similar fields, but this study demonstrates how minimal data can be used to robustly validate such a model. There is now scope to work in collaboration with the water industry to apply this to other sewer catchments, testing the underlying assumptions in new situations and evaluating the effectiveness of the model as a scoping tool to target sewers for further on-site investigation to confirm or rule out capture using the indication methodology put forward in Chapter 3.

6.2.5 Addressing the overall aims of the thesis

This study has successfully established that streams and springs have been captured into combined sewers, both through the literature and through a focused case study of a UK city. It is the first dedicated assessment in the academic literature of this issue, and clearly differentiates stream and spring capture from infiltration-inflow by the cause and the mode of entry.

The thesis has focused on developing methodologies and tools for use by the water industry to indicate where capture occurs, using multiple lines of evidence. This includes a novel water typing technique to detect captured water in the sewer. An expert knowledge BBN was developed to integrate the multiple lines of evidence to predict the likelihood of stream and spring capture and infiltration-inflow across a combined sewer network, suitable as a scoping tool for use by the water industry to quickly target areas for further tests to confirm capture.

The overall conclusion of the thesis is that stream and spring capture does occur and that the water industry should now apply the methods and tools across the UK in order to evaluate the true costs of stream and spring capture and the opportunities for management. The following sections will now discuss the implications of this research for the water industry and future management of sewer networks, as well as outline specific future research that can build on this work.

6.3 Implications for the water industry

6.3.1 Defining stream and spring capture

This thesis has considered stream and spring capture to be a distinct and separate cause of clean water entry into combined sewer systems, in addition to that defined as infiltration-inflow. It is important to reflect on whether it is correct to consider stream and spring capture separately in this way, when the same shallow groundwater and springwater will likely supply both the captured streams and springs and the infiltrating groundwater in many situations. This may be especially true for capture by conversion, where there may be no discrete inflow of a watercourse into a combined sewer (unlike with capture by interception), but where the entire watercourse has historically been converted into a combined sewer. It is possible – indeed, likely – that the local hydrological conditions would cause such sewers to experience greater volumes of infiltration-inflow through any pipe cracks or defective joints associated with the former watercourse bed where the watercourse was (or still is) a gaining stream. Furthermore, as reported by Read (2004), some combined sewers were historically designed with gaps between joints to drain groundwater, and those combined sewers deliberately sited to replace a stream or spring may have been designed in such a way.

There is therefore a degree of overlap between the concepts of stream and spring capture and infiltration-inflow, in terms of the source of water, the fact that capture may not always be mutually independent of infiltration-inflow, and the impacts once in the sewer. Critically, the definitions used in this study have differentiated capture as being intentional and being primarily associated with three modes of entry that are different to infiltration-inflow. For the purposes of this study, retaining this distinction has been important in order to draw attention to stream and spring capture specifically; though acknowledged in the literature, few studies explicitly focused on the causes, consequences or identification of capture, despite there being some important differences from infiltration-inflow.

This work has led to a conclusion that the conventional approaches to sewer rehabilitation, defect identification and leakage reduction may not tackle direct inflows of capture by interception, or help to specifically draw the link between infiltration-inflow caused by conversion of a watercourse into a combined sewer. Furthermore, retaining this distinction been a useful communication tool; the fact that water entering a combined sewer is perceived to be not just from an unspecific groundwater entity but from a specific lost stream or spring (that in some cases influenced the history of a local area), has evoked an interest and enthusiasm to look at this issue in a new way across the water industry, local authorities and the public, notably including the different restoration opportunities this presents, as highlighted by the Zurich case study.

Moving forward, however, it is now important to reconsider the definitions and distinction between stream and spring capture and infiltration-inflow. Hydrologically, it would be pertinent to look more closely at sites of suspected capture by conversion, to precisely identify how the water enters the combined sewer. In such cases, is it a diffuse entry through pipe cracks and defective joints along the bed of the lost stream, or is there a more discrete point of entry akin to capture by interception? Legislatively, the definitions may influence the requirement for any action, and should be considered carefully. Inclusion of stream and spring capture as a special subset of infiltration-inflow may fail to fully recognise the important differences in the causes, effects and management implications, but it might enable stream and spring capture to be more quickly and simply acknowledged and tackled under existing legal frameworks. This debate should not be settled at this stage: it would benefit from wider consultation with the water companies and river restorationists (and other stakeholders). A measure of the success of this study, however, will be whether it has helped to draw sufficient attention to this issue, and whether this debate will now be taken up.

6.3.2 Recommendations

This thesis has demonstrated that stream and spring capture may be worthy of consideration by the water industry as a source of clean baseflow to combined sewer networks, and that there are methods available to identify where it occurs. There are three key recommendations from this work.

First, the water industry (including the Environment Agency) should explicitly recognise stream and spring capture as a source of clean baseflow to combined sewer networks. This could be done by redefining the term infiltration-inflow to ensure it includes both unintentional ingress of groundwater baseflow into the combined sewer through pipe cracks and defective joints, as well as the intentional interception or conversion of watercourses into combined sewers or the intentional direct capture of springs into combined sewers. Point source inflows commonly considered under the term infiltration-inflow usually focus on the wet weather stormflow inputs to combined sewers; redefinition of the terminology should expand this to consider the baseflow element of capture too. This would acknowledge that there are similarities between infiltration-inflow and stream and spring capture: impacts on sewer capacity, increased baseflow to WwTWs, and the probable shared origin of shallow groundwaters that supply the captured streams and springs and infiltration-inflow. It would also acknowledge dissimilarities in the causes and entry mechanisms to the combined sewer, the unique detection methods required for capture, and consequently the different management approaches available. By redefining infiltration-inflow rather than keeping stream and spring capture as an entirely separate concept, it also ensures that stream and spring capture will fall under the immediate attention of existing efforts in research and industry to manage this issue.

The second recommendation is that the water industry should now evaluate stream and spring capture in other combined sewer networks. It should apply the capture indication methodology developed in Chapter 3 to locate lost streams and springs, indicate where capture may be occurring, including through the use of the water typing technique developed in Chapter 4, and verify capture where possible. The aim should be to determine whether capture occurs and where it occurs in combined sewer networks. The next challenge is to identify whether the sewers are at risk from capacity-related issues such as urban surface water flooding, sewer flooding, or CSO spills, whether network capacity upgrades are required, or whether there are elevated wastewater treatment costs. The BBN model developed in Chapter 5 may provide a useful scoping tool to integrate the evidence and strategically assess entire sewer networks, comparing whether sewers not previously considered at risk from infiltration-inflow through pipe cracks and defective joints may be at risk from captured streams and springs.

Third, the water industry should consider management options for captured streams and springs. This study has identified several sites in a case study catchment where capture by interception, capture by conversion and direct spring capture occur. Some cases have been confidently verified, and in other cases further field investigation methods are available to confirm or rule out capture. The review in Chapter 2 detailed the exemplar of Zurich, Switzerland, that has taken a long-term strategic approach to managing and separating captured streams and springs from the combined sewers, and reportedly has delivered wide ranging environmental, social and economic benefits. The use of daylighting and restoration of urban watercourses to separate the clean baseflow out of the combined sewers could therefore bring promising benefits not only to the water companies but to other authorities and organisations tasked with flood risk management, environmental quality and urban planning. There is a need now to robustly evaluate the types of management response available, consider the costs and benefits of action, and explore the potential challenges and barriers to implementation at sites where capture has been identified.

6.3.3 Management opportunities and barriers to change

Let us now consider what would be required for a water company in the UK to separate captured water from the combined sewer system, drawing on the research findings of this thesis to make recommendations and pose questions for further research.

Is there a business case to encourage water companies to separate captured streams and springs from the combined sewer system?

Chapter 2 summarised the range of impacts of stream and spring capture as increased capital and operational costs to water companies, and a number of environmental externalities that can result in fines to water companies (such as sewer flooding). Using a proxy of domestic wastewater charges, the cost of including a small captured watercourse with baseflow of 1 l/s in a combined sewer is £33,000 per year, compared to £10,000 per year if treated as stormwater. Given the findings of this thesis, there is an urgent need to quantify the baseflow contribution of the captured streams and springs that were identified using the methods developed in this study and then to refine these cost estimates in consultation with water companies and the regulator Ofwat. It stands that there is potential to considerably reduce costs associated with wastewater treatment, sewer upgrades, and incidents such as sewer flooding by separating the flow. The Zurich Stream Concept case study put a lower price on the cost of including captured streams and springs in combined sewers, but nevertheless economically justified long-term action to remove the captured water.

Budgets, water charges and investment programmes for water companies in England and Wales are set in consultation with the regulator Ofwat in five-year cycles. The current Price Review 2014 sets this for the 2015-2020 Asset Management Plan (AMP) period. In the previous AMP period, £22 billion was invested by the largest water companies in England and Wales on maintaining and upgrading assets (Ofwat 2010a). Any recommendations for action on stream and spring capture would need to fit into the AMP programmes, and a case should be made to demonstrate the role of stream and spring capture reduction as meeting drivers such as sustainability (particularly reducing energy costs at WwTWs) or sewer flood management. Consequently, further research may be needed to precisely quantify the costs and benefits of action to these strategic areas or business objectives.

Studies for Ofwat have considered the impacts of stormwater and infiltration-inflow on sewer flooding and CSO spills and have recommended reducing infiltration-inflow to tackle this (Halcrow 2013, Mott MacDonald 2011). Stream and spring capture was not recognised in these reports, but should now be included in future. SuDS reduce stormwater to combined sewer systems, reducing sewer flood risk and surface water flood risk. The slow progress of adopting SuDS into law (both to encourage uptake by water companies and to empower and enable the necessary stakeholders to install and maintain them) suggests that there may be a similarly slow process of recognition and adoption of measures to tackle stream and spring capture (Mott MacDonald 2008).

Indeed, economic savings of reducing clean baseflow from combined sewer systems may not be sufficient incentive alone for action by water companies. This thesis was introduced with the example of London's lost rivers, streams and springs that were deliberately captured into the Victorian interceptor sewers. Continued CSO spills, sewer flooding and other capacity-related issues have resulted in the controversial Thames Tunnel project – a new deep interceptor sewer beneath the River Thames that will relieve capacity in the current combined sewer system. The controversy is due to the high costs of this engineering project and the perceived lower cost alternative solutions such as retrofitting SuDS across the city (Ashley 2012). It also involves capacity upgrades at WwTWs. Former Ofwat director Sir Ian Byatt has openly criticised Thames Water for failing to tackle groundwater infiltration-inflow in London's ageing and degraded combined sewers, which he says has caused the interceptor sewers to flow nearly full during dry weather (Byatt 2013). The role of the lost and captured streams and springs has not been considered explicitly as contributing to this problem, nor has their separation to enable baseflow and stormwater to be diverted out of the combined sewers and back into natural watercourses once more. Until an independent review is available, it is difficult to comment further on the details of this project. Byatt goes on to argue: "Rather than rewarding the company with a large increase in its Regulatory Capital Value (RCV), regulatory action should be directed to getting the company to step up its sewer maintenance programme" (Byatt 2013: 1).

The RCV is important to water companies, as this determines the price limits they can set, and ultimately influences their profit margin and financial return to shareholders. It is possible to argue that where water companies are able to expand the sewer network (hence increasing their asset base) to accept elevated baseflow from infiltration-inflow or captured streams and springs, it disincentivises action to reduce the operational costs. Consequently, stream and spring capture becomes part of a wider debate on water company pricing and regulation, and engagement on stream and spring capture should integrate with existing dialogue on water industry policy. The current CEO of Severn Trent Water, Tony Wray, recently argued that the existing focus on increasing RCV must change in face of tightening regulation and consumer backlash against price rises; he recommended an industry-wide move towards reducing operational expenditure to improve environmental and economic sustainability in water companies (Wray 2013). If this were to happen, the business case for water companies to reduce stream and spring capture and infiltration-inflow may be strengthened. Currently, it appears as though there may be insufficient reward alone to encourage action by water companies.

Are there regulations that currently exist or that might be amended to compel a water company to separate captured streams and springs?

With stream and spring capture being a relatively new concept, there are no specific laws or policy statements that explicitly address it in the UK, but it may be covered under existing legislation relating to sewer design and management.

Legal drivers for UK water companies to reduce infiltration-inflow have been reviewed in several studies (Ellis 2001, UKWIR 2012). There are European and national UK standards (EN 752) that require the structural integrity and watertightness of sewers. This addresses infiltration-inflow in principle; in practice it is not being effectively adopted into UK planning and the water industry recognises the need to review the legislation and to have quantitative goals to limit infiltration-inflow (Orman 2008, Schulz and Krebs 2004, UKWIR 2012, Water UK 2010). Indeed, current standards and guidelines issued by the Secretary of State are more pragmatic: they explicitly acknowledge that infiltration-inflow cannot be entirely prevented in sewer networks, and require sewers to be designed with sufficient capacity to accept reasonably anticipated clean baseflow over the sewer lifetime (Defra 2011). Watertightness, however, cannot cover intentional inflows of captured streams and springs, despite having similar impacts to infiltration-inflow. Any review of legislation should recognise this.

The EU Urban Wastewater Treatment Directive (EC 91/271, Annex 1a) requires prevention of sewer leaks; this explicitly tackles the causes of infiltration-inflow through pipe cracks and defective joints, but not stream and spring capture. Moreover, it actually implies a focus on exfiltration – leakage of wastewater out of sewers into groundwater. The Directive also requires member states to set limits of CSO discharges based on the water quality impacts and sensitivity of receiving waters. This presents a legal framework by which more stringent regulation of CSO discharges could be used to encourage reduction in infiltration-inflow and stream and spring capture, where the increased clean baseflow exacerbates lack of sewer capacity for stormwater. This has not, however, resulted in such action in London as discussed above.

In the US, the Clean Water Act has driven reduction in infiltration-inflow to combined sewer systems to reduce CSO spills; an initial focus on technical solutions to waterproof pipes has given way to a more recent focus on strategic network management (Schantz 2005, UKWIR 2012). This is particularly evident in the recent proposals in Pittsburgh by water authority ALCOSAN, which has undertaken not only infiltration-inflow reduction, but also identified and planned removal of some watercourses directly intercepted into the sewer system, as outlined in Chapter 2 (ALCOSAN 2012, Troianos et al. 2008, US Army Corps of Engineers 2009).

Zurich appears to be unique in its explicit recognition of stream and spring capture in legislation, discussed in detail in Chapter 2. The Water Pollution Law 1991 was the key driver to require and empower the long-term strategy to separate the captured water from the sewer system. Such legislation may be required to drive change in the UK.

What is the case for action on captured streams and springs when considered beyond a water company perspective?

As outlined in Chapter 1, while stream and spring capture fundamentally impacts upon the water companies and hence should be first understood from this perspective, there are also implications for watercourse management. This introduces different stakeholders and responsible authorities in the UK; there is likely to be stronger case for action when the wider costs of stream and spring capture and benefits of managing it are considered. However, fragmented management in the UK arises from the numerous authorities responsible for the environment, fluvial flooding, surface water management, wastewater management, and urban planning. This complicates the management situation when stream and spring capture is considered beyond just a water company perspective; this has been similarly experienced in the development and adoption of SuDS in the UK (CIWEM 2013). In comparison, Zurich has one responsible unitary authority with the power to integrate wastewater management, flood risk, environmental restoration and urban planning associated with the separation of captured streams and springs.

A future vision for the UK might follow the Zurich example:

> Small streams and springs that had been captured into the combined sewer system could be daylighted and restored as natural watercourses through towns and cities. These will be used to convey clean baseflow to river networks, but stormwater may also be diverted into them. They will be designed as natural features that effectively restore aquatic and riparian habitats in urban areas, providing wildlife in the city. They will also be a key component of retrofitting SuDS to attenuate and filter pollutants from urban runoff; this will reduce stormwater flows to combined sewers, sewer flooding, CSO spills, and urban surface water flooding. They will be designed in such a way that does not present a new fluvial flood risk. By reducing the clean baseflow from combined sewers and WwTWs, the future management costs of sewer networks will be reduced, improving sustainability across the sector. This will be tied into a long-term strategy that is backed by legislation to enable and empower the water companies, Environment Agency, local authorities and other stakeholders to work together to undertake the design, construction and operation of these features. Many of the restored watercourses will be considered natural, but as in Zurich some cases would be possible only as artificial, engineered water features due to space or technical constraints. Through high quality architectural design, these may still offer a range of environmental, social and economic benefits, but may be recognised as assets owned and maintained by water companies.

If this vision were to be realised in the UK, then what is required?

There is an increasing body of work establishing the costs and benefits of stream daylighting and restoration, which is of relevance if the UK water industry were to adopt the approach taken in Zurich. There are widely reported environmental, social and economic benefits of restoring and daylighting culverted watercourses, including the following (Broadhead and Lerner 2013, Wild et al. 2011):

- aquatic and riparian habitat restoration;
- improved water quality, both directly through enhanced nutrient cycling and filtration by plants, and indirectly through making pollution visible;
- urban heat island mitigation;
- improved fish passage;
- reduced flood risk;
- amenity and recreation benefits;
- intrinsic, aesthetic and cultural benefits;
- reduced risk of culvert collapse, and lower maintenance or repair costs;
- enhanced land values as part of urban regeneration.

While these benefits may appear highly promising, there is a need to independently review and evaluate them; case study experience in the field of river restoration has demonstrated the difficulties in measuring some of these supposed benefits, and many projects do not robustly report the objectives and outcomes (Wild et al. 2011). It is especially important to review the reported experience from Zurich since the 1980s, where stream and spring capture separation through daylighting introduces new technical challenges beyond normal river restoration. Experience from Pittsburgh, where separation of stream and spring capture is currently underway, should also be independently reviewed.

This research has confidently identified several sites where different types of stream and spring capture occur in one case study catchment. A full technical feasibility as well as an evaluation of the costs and benefits could now be undertaken, that would quantify the current costs of the capture, investigate options to separate the capture, and evaluate them, not only for the water company but also for other key stakeholders. Even at this stage, it is possible to identify several complex issues that must be resolved:

- **Site PW**: an open watercourse flows downstream into a combined sewer (capture by interception).

- Is the upstream, open headwater reach considered to be a natural watercourse, and is the discharge into the combined sewer seen as a physical modification under the Water Framework Directive?
- At what point does the stream change its legal status to a combined sewer?
- Downstream of the point of capture, the remaining 1.5 km of watercourse has been entirely replaced by combined sewers – is there space for an open stream to be constructed or separate surface water pipe to be installed over this distance?

- **Site CV**: a culverted watercourse was replaced by a combined sewer but a discrete inflow from the reservoir is clearly visible (capture by conversion, capture by interception).
    - Is the legal status of this historical watercourse now a combined sewer?
    - Could the watercourse be reverted back to a natural *ordinary watercourse* (open or culverted) under local authority control?
    - Is it possible to divert the clean inflow from the reservoir into an open watercourse through the 700 m of parkland immediately downstream of here?
    - Could this help to reduce local surface water flood risk (see flood map) on site, and in surrounding areas, by diverting stormwater to the restored watercourse and attenuating it there?
    - What would happen over the last 500 m of the watercourse's original route to the downstream River Don? Would urban regeneration in this area benefit from the water feature? Would attenuation of baseflow and stormflows be of sufficient benefit that excess waters could then be reconnected back into the combined sewer?
- **Site HB**: a culverted watercourse that is labelled in the surface water sewer network flows to a combined sewer (capture by interception).
    - What is the legal status of the upstream culverted section? Is it a watercourse under local authority control, or a surface water sewer under water company control? At what point does this legal status change?

    - Is it possible to divert the clean water into a new separate surface water sewer or open watercourse for the 350 m to the downstream River Don?
- **Site SR**: numerous springs are likely to be draining to the combined sewer, and further downstream this sewer has replaced a watercourse (capture by conversion, direct spring capture).
    - There is no discrete inflow or remnants of a natural or culverted watercourse in this area, so is this sufficient evidence to recognise the historical watercourse in the area?
    - Is it possible to separate the wastewater from the captured water here? Would it require that the existing combined sewer be reverted to a surface water sewer and re-routed to the River Don by disconnecting wastewater connections? Would it be possible to find and divert all captured waters into a new separate surface water sewer or watercourse and convert the existing combined sewer into a foul sewer only?
    - If the legal status of the historical watercourse is entirely a combined sewer, then what would be the legal status of any restored watercourse and would it be recognised under the Water Framework Directive?

Chapter 2 also outlined the legislation on protection of headwater streams. In the US, one of the drivers for research has been the ambiguity in the Clean Water Act that has left small headwater streams unprotected (Elmore et al. 2013). Numerous studies have demonstrated the role of small headwater streams on downstream hydrology, water quality and ecology of downstream river networks (Alexander et al. 2007, Fritz et al. 2008, Gomi et al. 2002, Lowe and Likens 2005, Meyer et al. 2007, Nadeau and Rains 2007, Sadler Richards 2004, Wipfli et al. 2007). This has driven recent studies that have sought to quantify the extent of headwater stream burial, showing that in both urban and agricultural landscapes many headwater streams have been culverted, dewatered or piped as surface water sewers (Bishop et al. 2008, Brooks and Colburn 2011, Elmore et al. 2013, Elmore and Kaushal 2008, Freeman et al. 2007, Pennino et al. 2014, Roy et al. 2009, Stammler et al. 2013). At the time of writing, the US Environmental Protection Agency (EPA) and US Army Corps of Engineers are proposing a clarification of the Clean Water Act to explicitly recognise headwater streams as watercourses; this will recognise the importance of and protect headwater streams from further burial and degradation (U.S. Environmental Protection Agency 2014). Although stream burial does not necessarily imply capture into combined sewer systems, the associated loss of urban streams from the urban environment is similar to stream and spring capture.

In the EU, there has been a similar discussion over stream burial of headwaters and the impacts of this (Bishop et al. 2008), and it is likely that headwaters such as this are currently not adequately protected under the Water Framework Directive (Lassaletta et al. 2010). If so, then this may apply to streams and springs that have not only been buried but also captured, and there may be new challenges for any attempts to separate them from the combined sewer system. Are captured watercourses protected in any way? What would they become once separated and restored? Would they become naturalistic but artificial features like SuDS, or natural watercourses, or would this depend on their design? Who would own, maintain or otherwise have legal responsibility for these features? If the potentially high number of lost and captured streams are recognised as watercourses, would this place an unfair burden on meeting the Water Framework Directive goals?

6.4 Further research

This study has raised a number of questions and there are four key areas for further research that are recommended, in order of priority:

1. **Technical feasibility and viability assessment of management solutions.** This thesis has demonstrated that capture is worthy of further attention by the water industry, and the next step should be to investigate the full costs and consequences of capture and the technical feasibility of management opportunities such as daylighting to separate captured streams and springs from the combined sewers. The capture sites identified in this study would be suitable starting points, because they include all three different types of capture. At this stage, the assessment would enable the water industry to explore whether the benefits and costs of action outweigh the impacts of capture on the sewer networks, and inform the water industry whether this is worth further consideration. There are technical challenges to address with this research. First, how can streams and springs be separated from the combined sewer? In cases where there is no discrete inflow that can be diverted

into a new separate surface water sewer or open watercourse, then it may require wastewater connections to be diverted to a new foul sewer in order to identify the precise source of clean baseflow. Second, is there space to separate the water from the sewers using stream daylighting in dense urban areas, and is this acceptable to the public and other stakeholders? Third, how might the wider ecological or flood risk benefits of daylighted streams used to separate the water be maximised whilst limited by constraints on costs or land take? There are also a number of policy questions that further research should address, including which organisations or authorities are responsible for separating captured streams and springs, and what regulatory changes may be required to promote action and to empower these stakeholders to work together to maximise the wider benefits.

2. **Hydrological assessment of flow from lost streams and springs.** This thesis developed methods to identify where capture occurs, but did not explicitly investigate the hydrology of lost streams and springs. This is now an important area for further research to complement the research into management opportunities. This is important, because if many lost streams and springs have been dewatered through changes to urban recharge or abstraction in the catchment, then they may no longer be flowing. A hydrological study would seek to test the flow of lost streams and springs, to assess the seasonality of their baseflow and their wet weather contribution to the combined sewers. For catchments similar to the case study catchment in this thesis, this is likely to require an assessment of recharge rates to groundwater, the exact locations and flow mechanisms of shallow and deep groundwaters, and how they contribute to springs and streams. It could involve predictive modelling of likely lost stream flows based on approximate channel size, or based on proxies of nearby open watercourses from similar geology, or it could apply field investigations including test boreholes and groundwater modelling to map and predict groundwater flows to lost streams and springs. Development of a tool to estimate the flow of lost streams and springs and the integration of this into the existing methodologies would help water companies predict the quantity of captured water to combined sewers, which would underpin network-wide cost-benefit assessment of impacts and management opportunities.

3. **Wider application to new combined sewer networks.** This study has developed methods that should now be applied in other combined sewer networks. This should be done in collaboration with water companies to access data and apply the various lines of evidence comprehensively to the sewer networks. The purpose of this is twofold. First, it is to test the methods and individual lines of evidence in different catchments. For example, topographic flowpath modelling may be less suitable in areas of flatter topography, and may result in higher uncertainty of capture likelihood. Second, it is to provide a national level assessment on the extent of stream and spring capture. In particular, it is important to know how prevalent capture is, and how many combined sewer networks it affects. It is also of interest to know whether capture is related to the age of the sewer network, the size of the town or city, or factors influencing the water and drainage such as topography, geology, or climate. It is also of interest to expand the search beyond the UK; many countries use combined sewer networks, and examples were found from around the world where captured streams and springs have been reportedly captured. Do the lines of evidence and methods developed in this study apply beyond the UK?
4. **Further application of major ion water typing.** It would be of interest to apply the major ion and minor ion water typing method to detecting infiltration-inflow, and to detecting stream and spring capture where a specific end-point is not clearly identifiable for sampling. This would require testing in new catchments where there is a more predictable water chemistry of groundwaters, rather than the highly spatially heterogeneous water types in this case study. Benchmarking of this against other tests that use one individual marker and flow rates would test its comparative performance in a way that has not been attempted yet. It could then be usefully evaluated for performance, reliability, practicality and costs compared to other techniques, both when applied to captured streams and springs and to infiltration-inflow. Inclusion of flow metering in collaboration with the water industry would enable the technique to quantify the volumes of capture in addition absolutely rather than relatively.
5. **Further development of the BBN.** Eliciting knowledge from more experts (including from academia, water companies, consultancies and local authorities) would

strengthen the BBN. It would enable a thorough characterisation of the state of expert knowledge on stream and spring capture and on infiltration-inflow, which could be used to quantify the uncertainties and target future research. There may be a number of ways to refine the BBN too, including improved knowledge elicitation formats (e.g. interviews rather than questionnaires to reduce the cognitive burden on experts), using consensus and workshops rather than simple averaging to aggregate expert knowledge, and direct inclusion within the model structure itself of variables representing additional lines of evidence and tests to indicate or confirm capture.

6.5 Summary of key conclusions

- Stream and spring capture has until now not been explicitly considered in academic literature or by the water industry as a source of clean baseflow to combined sewer networks, but evidence suggests it does occur in combined sewer networks around the world.
- Stream and spring capture is likely to have similar impacts to infiltration-inflow that are relevant to the water industry, increasing clean baseflow to combined sewers and WwTWs. It also presents unique additional environmental, social and economic impacts associated with the loss of urban watercourses; this is of wider relevance to fields including urban planning, surface water flood risk management, and environmental and ecological management.
- Water industry consideration of infiltration-inflow does not adequately recognise stream and spring capture at present, and this must be addressed in policy and action.
- Stream and spring capture has different causes to infiltration-inflow; it therefore may affect different sewers and will require different approaches to identify where it occurs.
- This thesis presents the first focused methodology to identify where stream and spring capture occurs. Multiple lines of evidence must be used because no single test can infallibly confirm or rule out all types of capture.

- Major and minor ion water typing can successfully identify captured water mixing in combined sewers. This is the first time this technique has been applied to either capture or infiltration-inflow. A number of issues have been identified that may limit its effectiveness in practice, and it would be useful to further develop this method in new catchments and fully compare it to existing techniques used to identify infiltration-inflow.
- A BBN modelling approach using expert knowledge is able to predict sewers that have a higher likelihood of stream and spring capture, providing a useful scoping tool for water companies to target sewers for further investigation to confirm or rule out capture. A key strength of the BBN approach is the explicit inclusion of uncertainty in the modelling, and the ability to integrate multiple lines of evidence and limited data with subjective experience and knowledge from academics and practitioners that is rarely available in the published literature.
- The BBN shows that capture is likely to be occurring in sewers not always affected by infiltration-inflow, suggesting that the water industry should in future consider stream and spring capture in their evaluation of sewer networks.
- In the case study catchment, over half the total stream length may have been not only culverted but entirely lost beneath the urban area. While some lost streams may flow to the river network in unmapped culverts or separate surface water sewers, several were confirmed through the methods outlined in this thesis to be captured into the combined sewers.
- In the limited examples of stream and spring capture being managed, options include separating the captured water from the sewers using watercourse restoration and stream daylighting. Such techniques are not addressed through the conventional rehabilitation of sewer pipes to reduce infiltration-inflow, and based on the findings of this thesis there is a strong case to now consider the costs and benefits of such solutions in more detail. This evaluation could be undertaken at the confirmed instances of stream and spring capture discovered in this thesis.
- The water industry should now apply and further refine the methodology developed in this thesis to examine the costs and consequences of stream and spring capture and management opportunities across the UK and beyond.

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Appendices

Appendix A

A selection of the non-georeferenced historical maps of Sheffield used in this study.

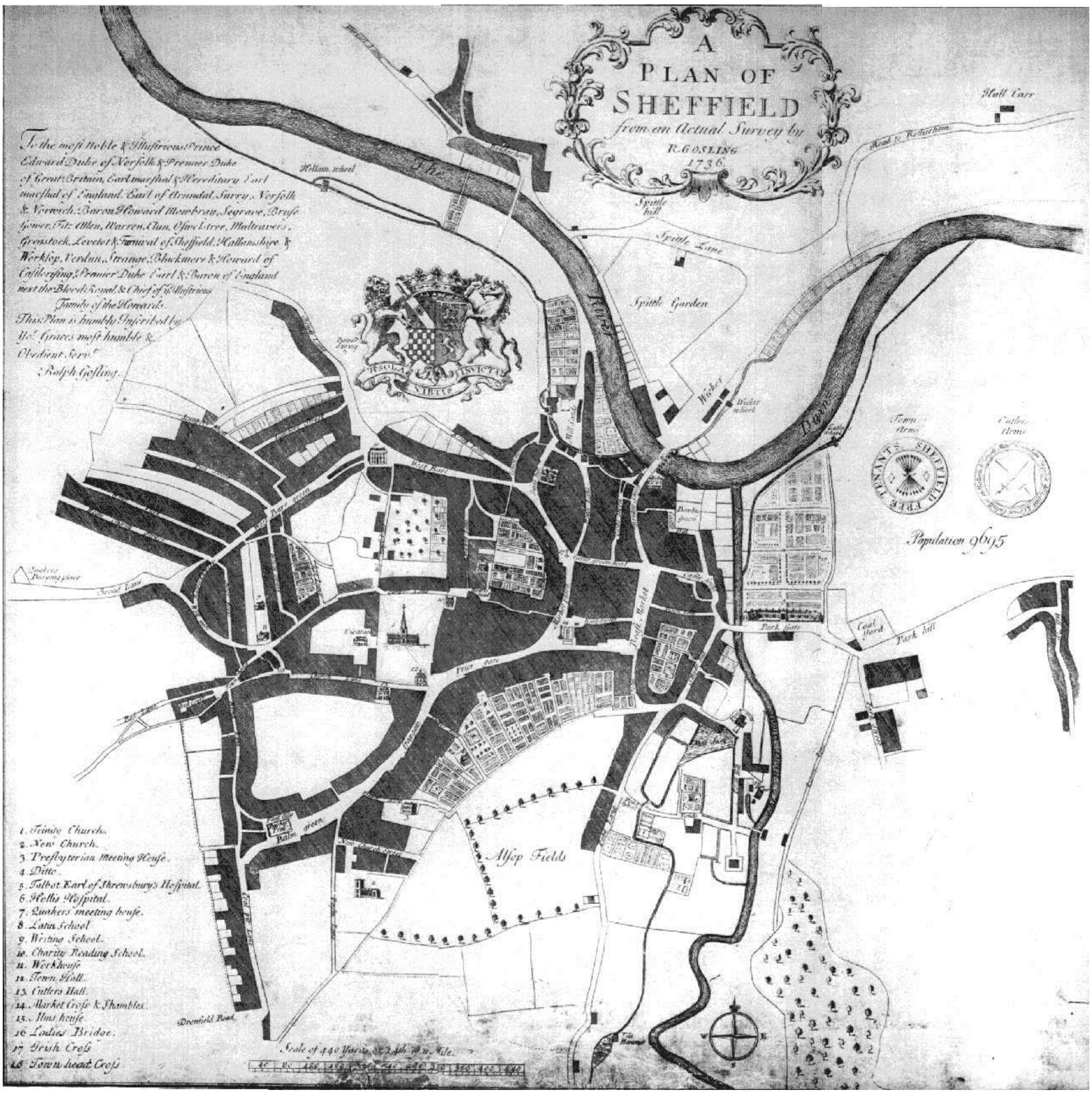


Figure 40 Gosling, 1736. Useful baseline to chart urban development, but does not indicate presence of streams and springs in the city area apart from the Porter, Sheaf and Don.

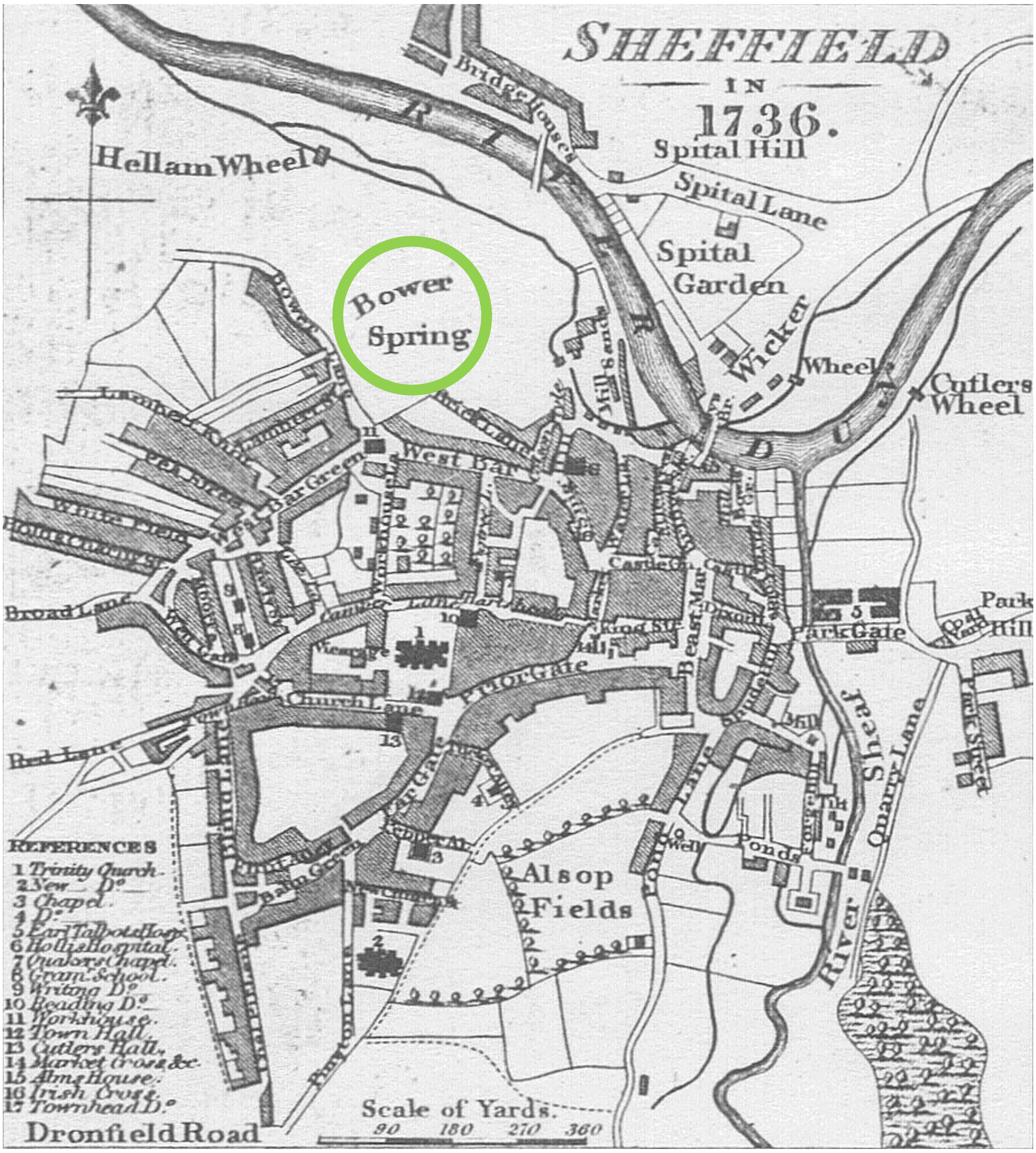


Figure 41 Uncredited, 1736. Bower Spring appears to the north of the city, which disappears in later maps.

Figure 42 Fairbank, 1771. Barker's Pool is marked, which at this time was created as a fire fighting water resources. Presumably it was fed by spring or stream, though none are marked. It was later filled in.

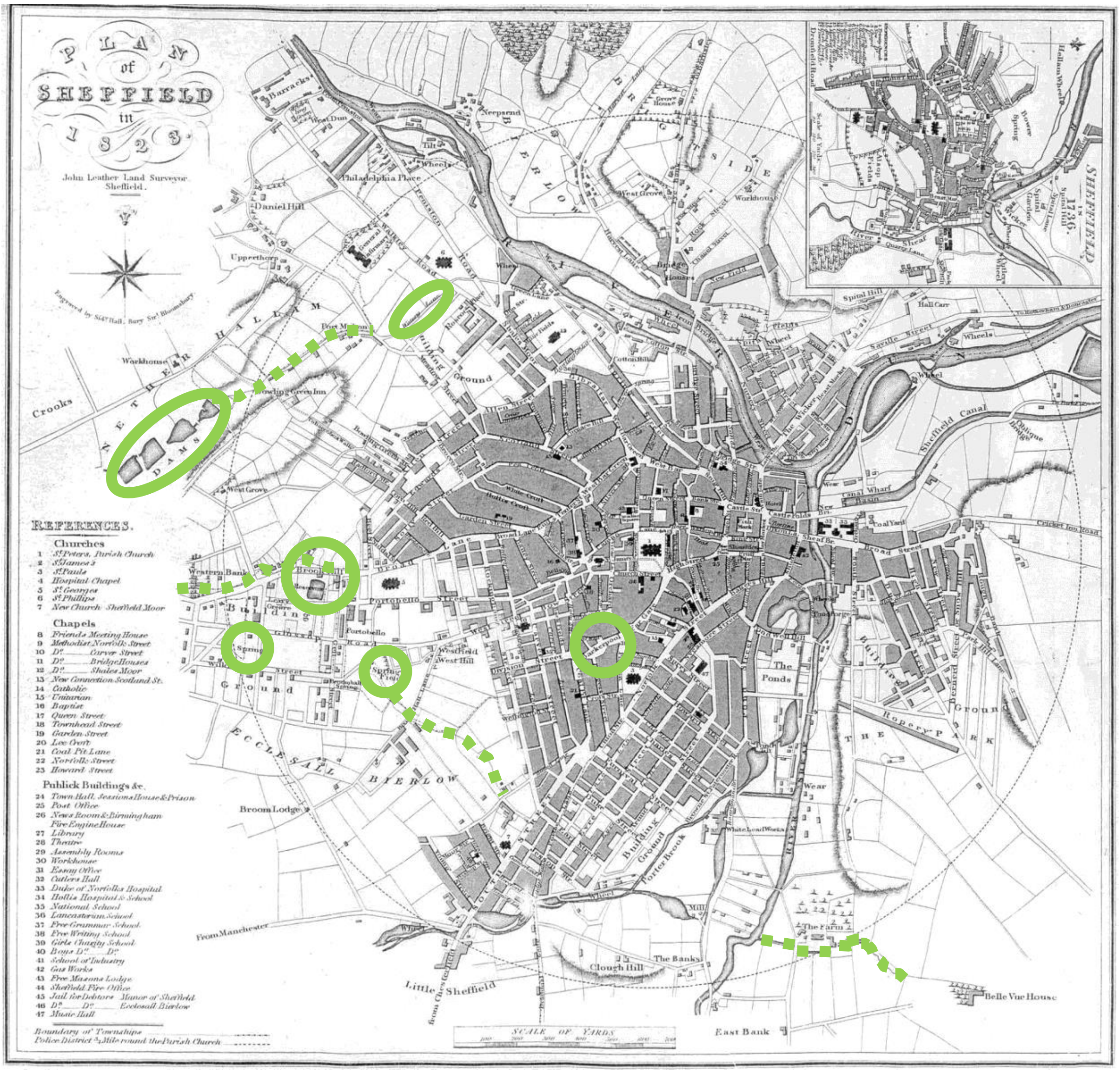


Figure 43 John Leather Land Surveyor, 1823. The stream below the dams in Crookes is visible, and although it disappears, Watery Lane is clearly marked. Several springs are marked, and two have likely stream paths delineated by curved field boundaries. The stream on Brook Hill is clear at this point; it disappears towards Broad Lane, but its path is detected in later maps.

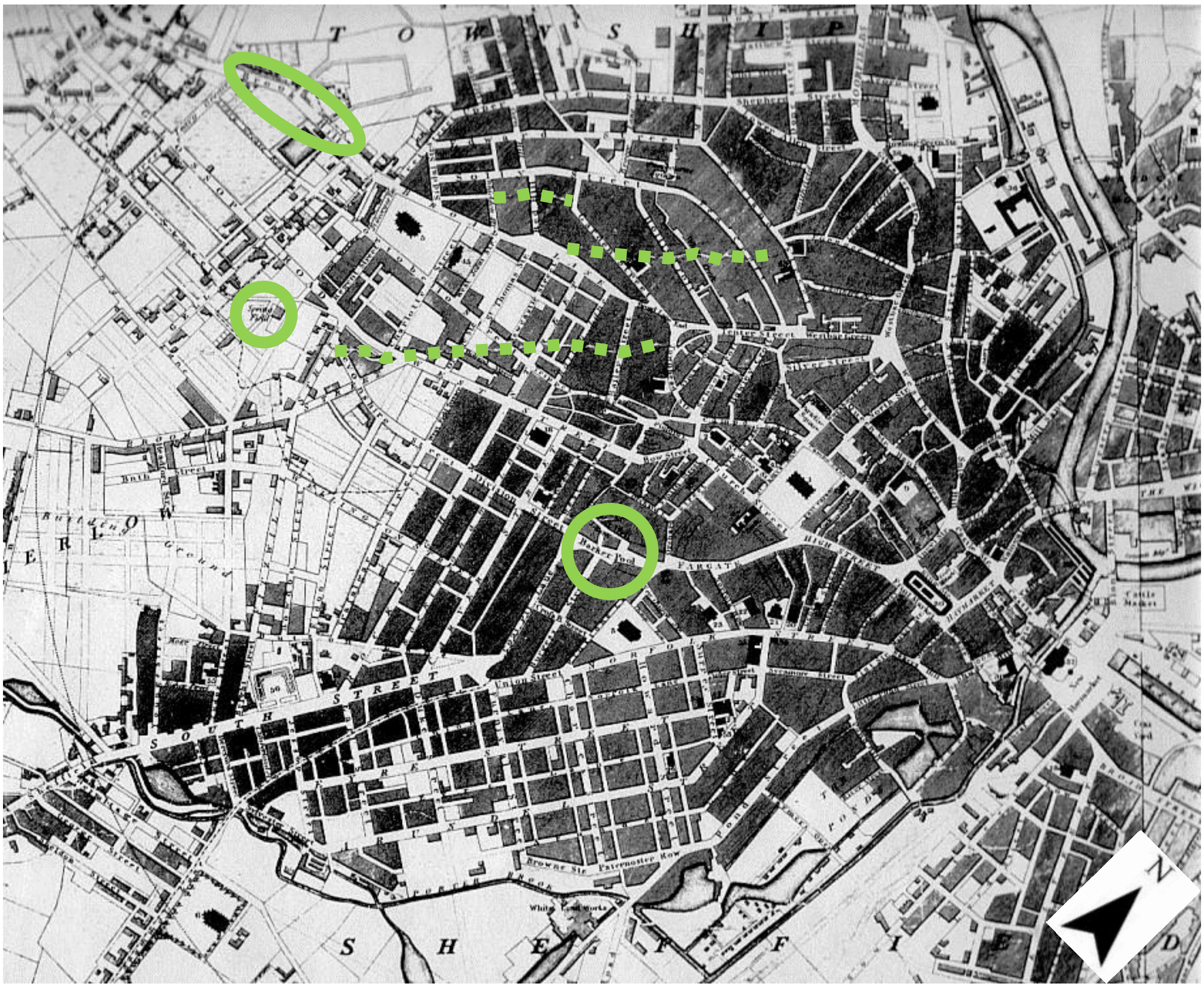


Figure 44 Uncredited, 1832. Subtle gaps in the blocks of urban development indicate the presence of either paths or streams, and due to their proximity to Spring Field and Brook Hill, streams are possible though not clear.

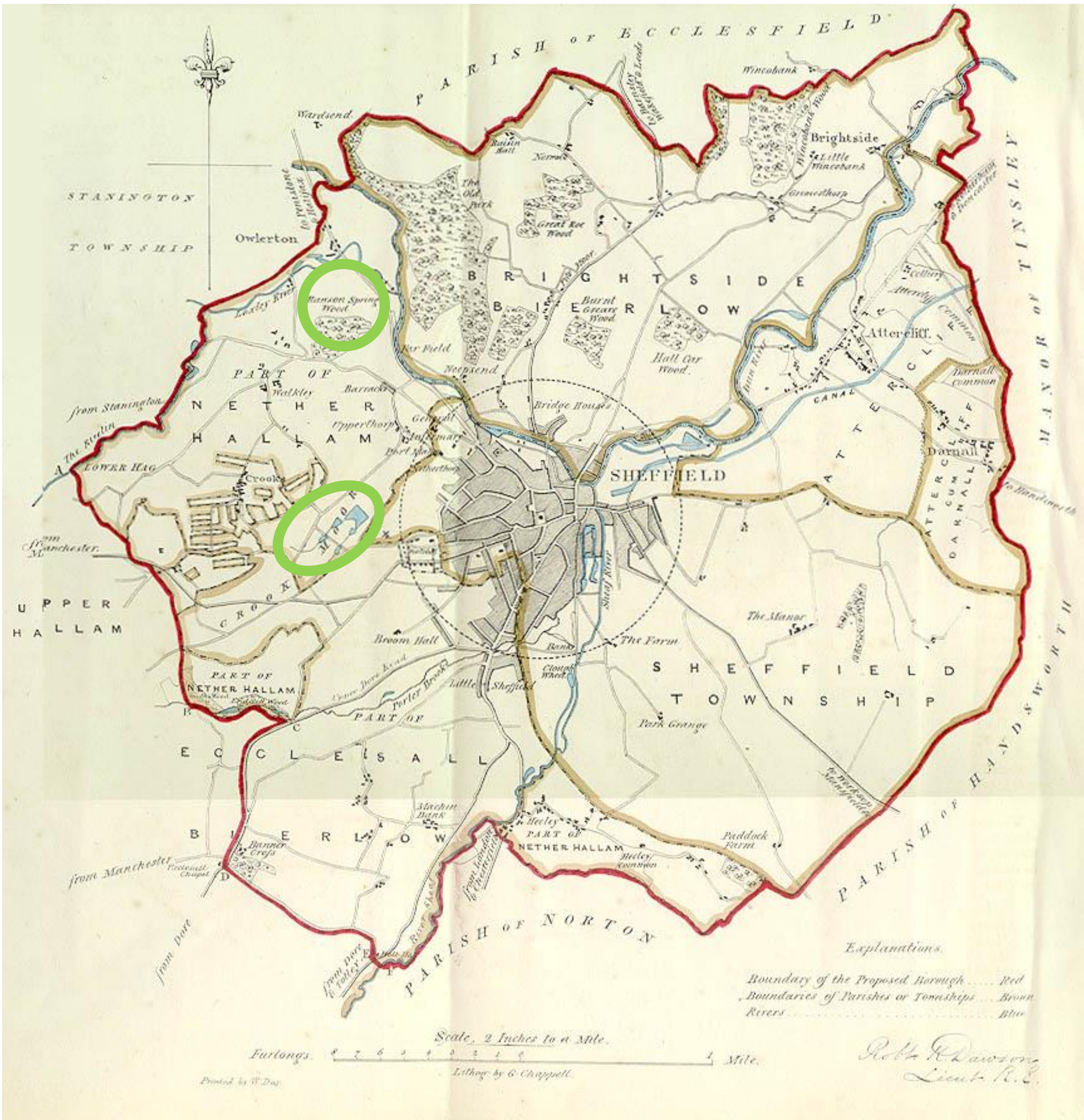


Figure 45 Lt. Robert Kearsley Dawson, 1832. The last Sheffield map before the more widely available Town Plans and County Series. Streams and springs are not clearly marked aside from the larger ones which still remain today. A place name on the outskirts takes its name from a spring.

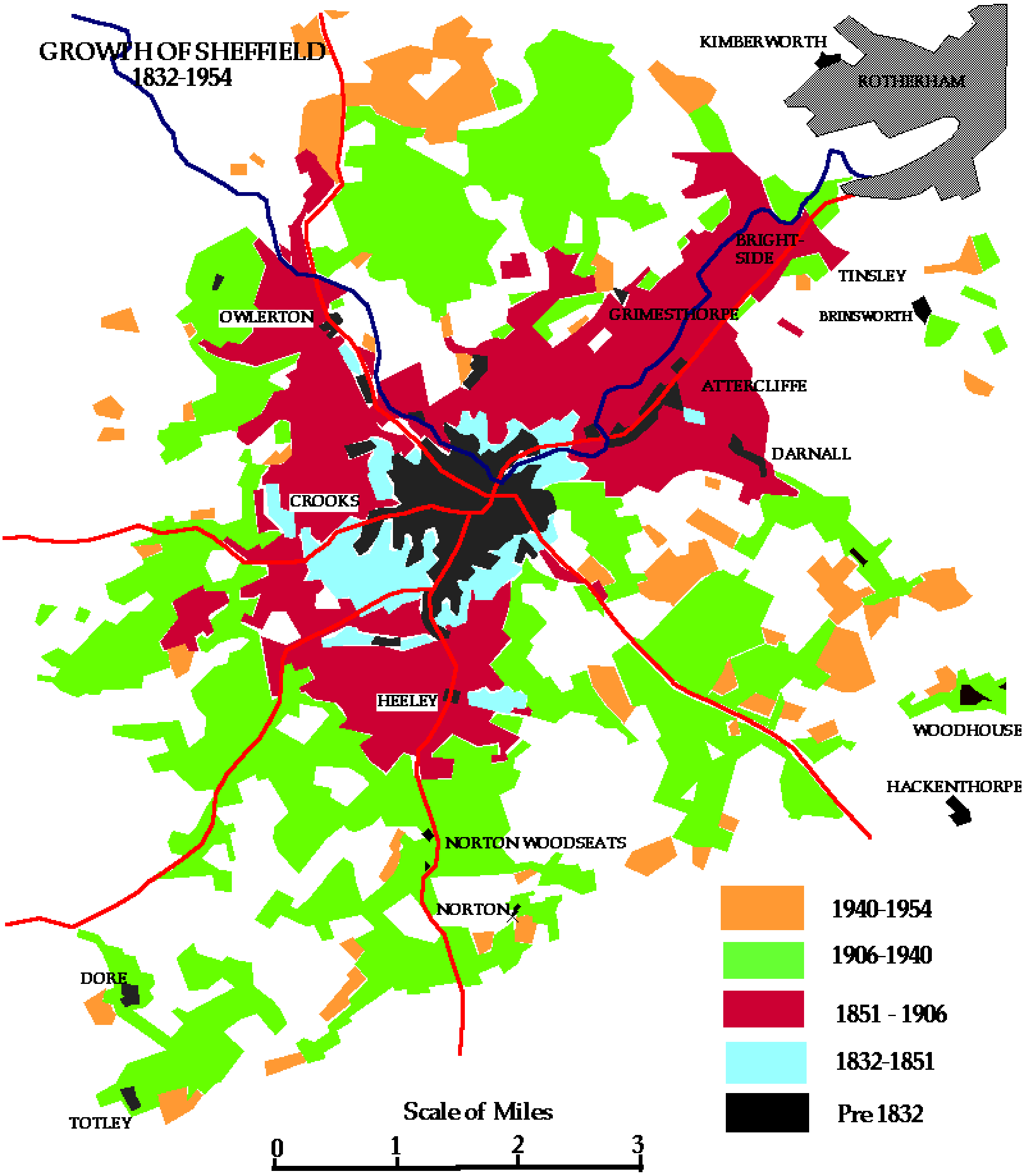


Figure 46 The growth of Sheffield 1832-1954 (http://history.youle.info/images/sheffield_growth.gif). The blue and red areas showing rapid urban expansion during the mid to late nineteenth century indicate locations where Victorian sewers may have first been laid at this time. These would likely have been combined sewers, and importantly, the first areas to be built on rural landscape, and therefore would have required small streams, drains, springs, seeps and issues to be managed.

Appendix B

Some paintings and images used as evidence of lost streams and springs in Sheffield.

Figure 47 Top: "Dam House, Crookesmoor, Sheffield" by William Ibbitt 1858. Image copyright, used with permission from Museums Sheffield. Below: view of Dam House today at Old Great Dam, Crookemoor, with reservoirs behind this now built over (photo by author).

Figure 48 "Street flushing near Barkers Pool in the 18th century", showing the use of stored spring water at Barker's Pool to flush open street drains in the city (Leader 1901). Image copyright, used with permission from Sheffield City Council Local Studies Library.

Figure 49 "Port Mahon Baptist Church (extreme left), Watery Street looking towards International Twist Drill Co. Ltd and Meadow Street”. This shows perhaps one of the last remaining open sections of the watercourse through Crookes Valley in 1966, now a combined sewer. Photo taken by H. Ainscough, 1966. Image copyright, used with permission from Sheffield City Council Local Studies Library and Mr D. J. Ainscough.

Appendix C

Night time minimum flow assessment

This section provides an overview of the methodology behind the data processing and interpretation of the sewer hydrograph night time minimum flow assessment, in support of the summary given in the text in Chapter 3.

HawkEye flow monitors were installed in Sheffield and processed by IETG on behalf of Yorkshire Water. Data were provided by as a 10 minute interval time-series of flow depth (mm, to nearest mm) and velocity (m/s, to 2 decimal places) at 24 combined sewer flow monitors between February and September 2011. The monitors can experience ragging when the sensor is obscured by solids, and the data reveal many instances where either recorded velocity or depth are zero unexpectedly due to other logging and blockage errors. Sewer shape and dimensions are provided in Yorkshire Water's sewer network data. For each monitor, flow rate was calculated simply from the depth, velocity and cross-sectional flow area.

The majority of pipes are circular, and cross-sectional flow area (*A*, mm^2) is calculated as:

$$A = \frac{1}{2}.\left((2\cos^{-1}\frac{R-h}{R}) - \sin(2\cos^{-1}\frac{R-h}{R})\right).R^2$$

where *R* is the pipe radius in mm; *h* is flow depth in mm.

Cross-sectional flow area (*A*, mm^2) of egg and arch shaped sewers are approximated as upright or wide (respectively) elliptical segments, a reasonable assumption for pipe flow less than half the depth (as the focus is on low dry weather flows):

$$A = \frac{ab}{4}\cdot\cos^{-1}\left(\left(1-\frac{2h}{a}\right) - \left(\left(1-\frac{2h}{a}\right)\cdot\sqrt{\left(\frac{4h}{a}\right)-\left(\frac{4h^2}{a^2}\right)}\right)\right)$$

where *a* is pipe height in mm; *b* is pipe width in mm; *h* is flow depth in mm.

Cross-sectional areas are then used to calculate the flow (*Q*, l/s) at each time-step:

$$Q = \frac{v.A}{1000}$$

A dry weather flow period from 17th April to 27th April 2011 was selected from the time-series of sewer flow data, using rainfall data supplied by University of Sheffield's Green Roof project (standard rainfall gauge) (**Figure 50**).

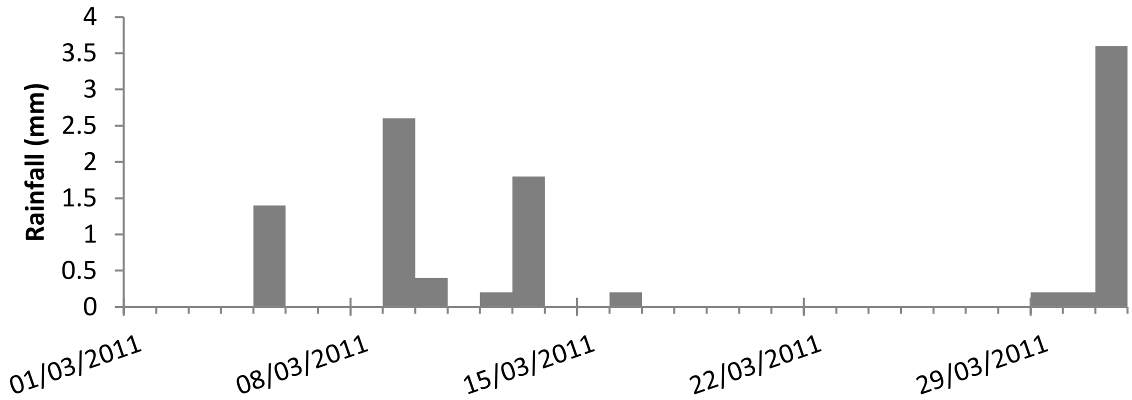


Figure 50 Sheffield rainfall data for a part of the sewer flow monitoring time-series to support the selection of a dry weather flow period (data courtesy of University of Sheffield Green Roof Project).

Each sewer flow monitor location is qualitatively interpreted with regard to the maps of lost streams and springs to predict whether captured flow may be expected or not (**Table 24** and **Figure 51**). The flows during the selected dry weather flow period were then assessed simply to calculate the total night time minimum flow as a % of the diurnal flow range, using a 24 point moving pass filter to reduce the high frequency noise associated with sewer flows and to extract the underlying diurnal patterns (**Figure 52** and **Table 24**).

Table 24 Sewer flow monitor summary analysis of night minimum flows.

Sewer monitor	Sewer close to lost streams or springs (capture expected?)	Night minimum flow (l/s)	Night minimum flow as % of diurnal range
F0824	No	1-2 l/s	50%
F0826	No	1 l/s	20%
F0829	No	1 l/s	25%
F0833	No	10 l/s	40%
F0834	No	0.5 l/s	25%
F0835	No	2 l/s	33%
F0836	No	4 l/s	50%
F0839	No	0.25 l/s	14%
F0840	No	4 l/s	29%
F0843	No	0.75 l/s	8%
F0848	No	0.3 l/s	20%
F0855	No	9 l/s	82%
F0856	No	5 l/s	42%
F0860	No	0.2 l/s	2%
F0876	No	1 l/s	33%
F2009	No	0.1 l/s	13%
F0830	Yes	25 l/s	63%
F0831	Yes	15 l/s	50%
F0832	Yes	7 l/s	44%
F0837	Yes	1.5 l/s	30%
F0838	Yes	0.5 l/s	33%
F0847	Yes	3.5 l/s	57%
F0850	Yes	20 l/s	50%
F0854	Yes	6 l/s	46%

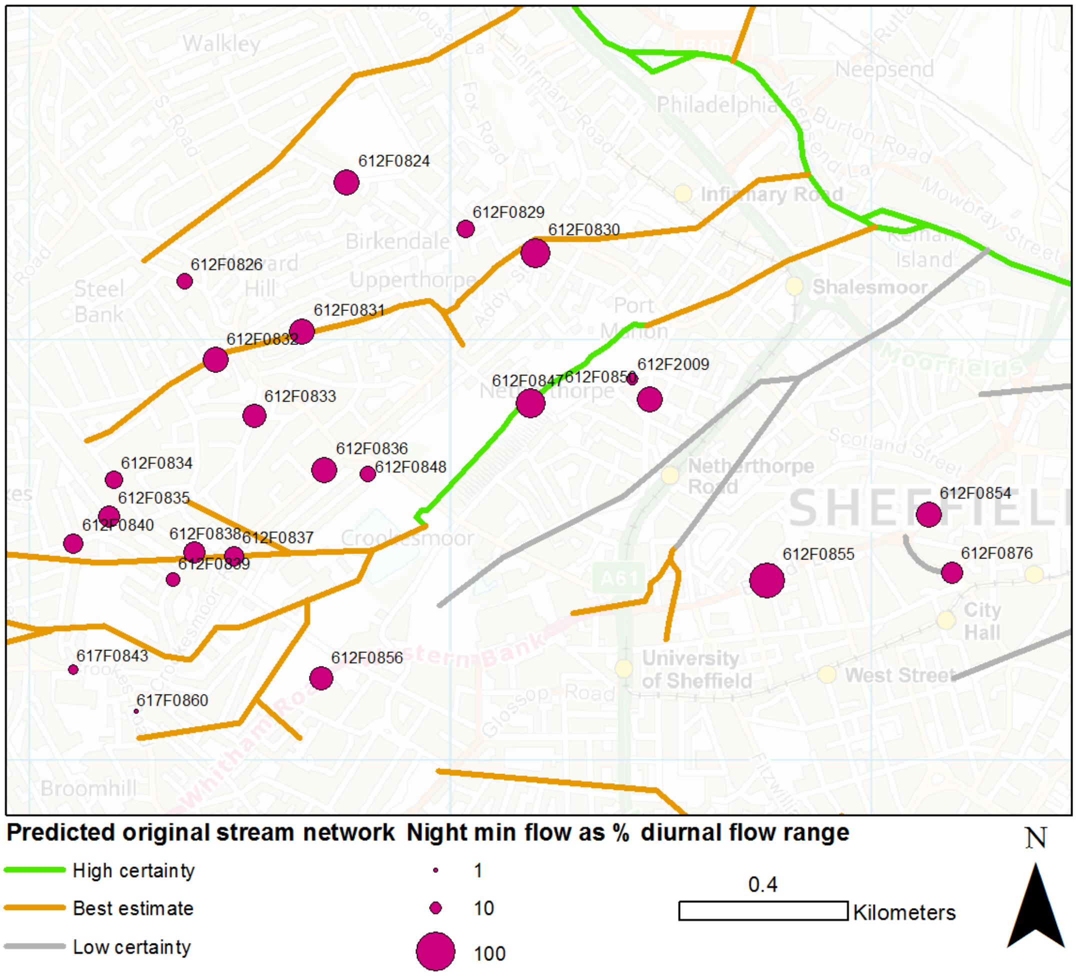


Figure 51 Sewer flow monitor locations (shown scaled as night time minimum flow as % of diurnal flow range) compared with the locations of lost streams in the area.

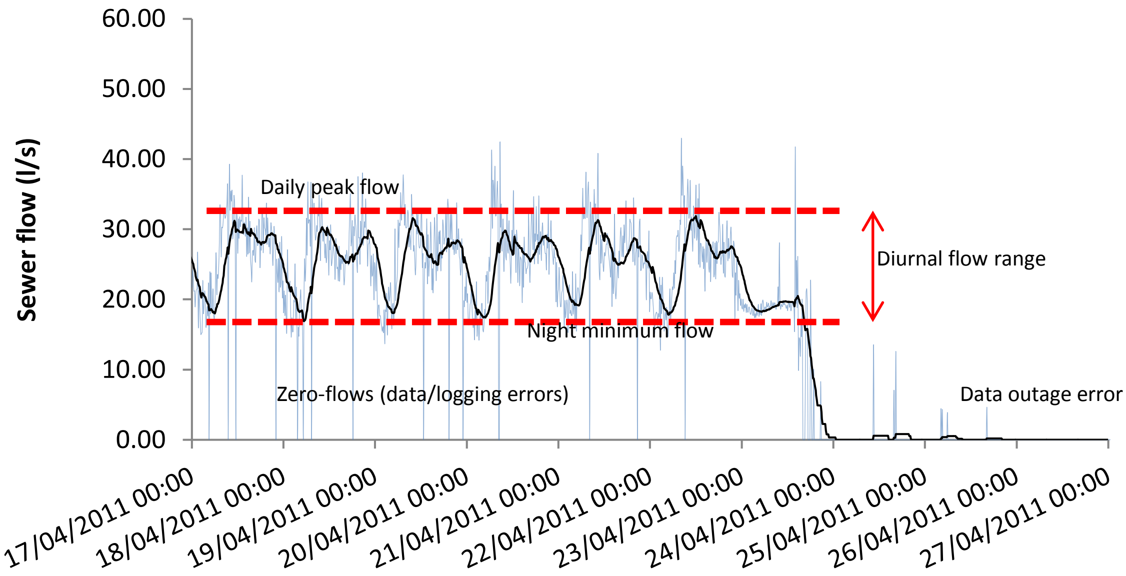


Figure 52 Night time minimum flow analysis illustrated for sewer flow monitor F0831, showing the flow time-series with a 24 point moving pass filter that reduces the high frequency noise to extract the diurnal pattern. Night minimum flow and daily peak flow lines are visually fitted, and the night minimum flow as a % of the diurnal flow range is calculated.

Sewer water balance

This section provides an overview of the methodology behind the data processing and interpretation of the sewer water balance assessment, in support of the summary given in the text in Chapter 3.

At a Springvale Road sub-catchment, a water balance is possible because sewer flow monitoring points and water supply inflow and outflow data for a District Metering Area spatially align reasonably well to account for almost all of the possible inflows and outflows. The water balance is:

outflow = (inflow – losses) + captured flow

Sewer flow monitor F0832 (**Figure 51**) is located on the only trunk sewer flowing out of this sub-catchment; any tapwater-derived wastewater and any drainage water will likely pass through this sewer monitor. The inflow of tapwater into District Metering Area J806 is recorded at a monitor situated at the upstream-most watershed boundary of this sub-catchment, and all flows in this J806 drain via sewer F0832. Additional tap water inflows also enter at this upstream end via a proportion of District Metering Area J845; using topographic maps, the portion of this District Metering Area that drains via sewer F0832 is measured ($J845_{edit}$), and given that the distribution and type of housing is considered uniform across this District Metering Area, the tap water inflows are split based on a straightforward area weighting (17%). Water losses to evapotranspiration, water exporting, percolation into groundwater and so on are not possible to quantify here, and are assumed to be zero; the results must therefore be treated with caution at this stage. The water balance therefore becomes:

outflows = (inflows – losses) + captured flows

F0832 = (J806 + $J845_{edit}$ – 0) + captured flows

captured flow = F0832 – (J806 + $J845_{edit}$)

Flow data were analysed for 17th and 18th April 2011 during a dry weather flow period (**Figure 50**), and are presented in **Table 25**. During this two day dry weather period, the average captured flow derived from the water balance is approximately 40% of the sewer flow. This analysis is shown, acknowledging the limitations, as a demonstration of the principle; to have greater confidence in the results themselves, it would require more sites where the inflows and outflows are adequately aligned based on the locations of sewer flow monitors and tap water District Metering Areas.

Table 25 Water balance calculations for Springvale Road sub-catchment.

Date and time	Outflow, hourly average at F0832 (l/s)	Inflow, hourly average at $J845_{edit}$ (l/s)	Inflow, hourly average at J806 (l/s)	Captured flow, hourly average at F0832 (l/s)	Captured flow (as % sewer outflow at F0832)
17/04/2011 00:00:00	9.39	0.79	4.4	4.21	45%
17/04/2011 01:00:00	9.59	0.71	3.7	5.21	54%
17/04/2011 02:00:00	8.42	0.69	3.6	4.13	49%
17/04/2011 03:00:00	7.66	0.67	3.5	3.51	46%
17/04/2011 04:00:00	7.76	0.69	3.4	3.65	47%
17/04/2011 05:00:00	8.65	0.76	3.7	4.16	48%
17/04/2011 06:00:00	9.22	0.99	4.7	3.53	38%
17/04/2011 07:00:00	14.00	1.39	6.8	5.84	42%
17/04/2011 08:00:00	16.45	1.69	9.1	5.67	34%
17/04/2011 09:00:00	17.27	1.83	9.3	6.11	35%
17/04/2011 10:00:00	15.62	1.82	8.3	5.47	35%
17/04/2011 11:00:00	15.39	1.66	8.2	5.54	36%
17/04/2011 12:00:00	14.46	1.46	7.6	5.45	38%
17/04/2011 13:00:00	13.26	1.30	6.8	5.19	39%

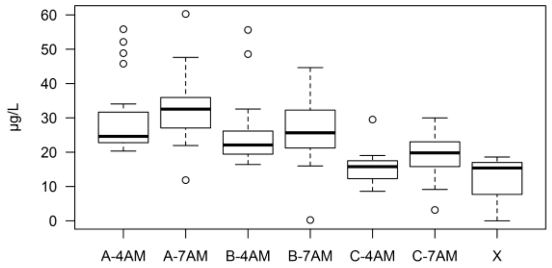
17/04/2011 14:00:00	12.47	1.30	6.3	4.92	39%
17/04/2011 15:00:00	10.90	1.35	6.0	3.54	32%
17/04/2011 16:00:00	12.32	1.36	6.7	4.30	35%
17/04/2011 17:00:00	13.02	1.57	6.9	4.52	35%
17/04/2011 18:00:00	13.66	1.56	7.4	4.68	34%
17/04/2011 19:00:00	13.54	1.39	7.4	4.74	35%
17/04/2011 20:00:00	13.09	1.30	6.6	5.17	39%
17/04/2011 21:00:00	12.80	1.34	6.3	5.21	41%
17/04/2011 22:00:00	11.04	1.09	5.6	4.34	39%
17/04/2011 23:00:00	9.06	0.84	4.4	3.82	42%
18/04/2011 00:00:00	8.12	0.74	3.7	3.67	45%
18/04/2011 01:00:00	7.11	0.70	3.3	3.10	44%
18/04/2011 02:00:00	7.79	0.69	3.1	3.96	51%
18/04/2011 03:00:00	6.91	0.69	3.0	3.18	46%
18/04/2011 04:00:00	7.38	0.74	3.2	3.41	46%
18/04/2011 05:00:00	9.66	1.01	4.5	4.17	43%
18/04/2011 06:00:00	14.97	1.78	7.5	5.70	38%
18/04/2011 07:00:00	15.46	1.90	8.5	5.03	33%
18/04/2011 08:00:00	16.28	1.64	8.2	6.46	40%
18/04/2011 09:00:00	15.01	1.52	7.7	5.81	39%
18/04/2011 10:00:00	14.22	1.35	7.4	5.50	39%
18/04/2011 11:00:00	11.18	1.23	6.4	3.51	31%
18/04/2011 12:00:00	12.06	1.20	6.5	4.41	37%
18/04/2011 13:00:00	11.75	1.10	5.9	4.72	40%
18/04/2011 14:00:00	9.97	1.13	5.5	3.37	34%
18/04/2011 15:00:00	11.06	1.20	5.4	4.51	41%
18/04/2011 16:00:00	10.80	1.35	6.2	3.30	31%
18/04/2011 17:00:00	13.27	1.53	7.3	4.44	33%
18/04/2011 18:00:00	13.77	1.57	7.3	4.94	36%
18/04/2011 19:00:00	12.88	1.42	6.8	4.65	36%
18/04/2011 20:00:00	13.62	1.33	6.9	5.42	40%
18/04/2011 21:00:00	15.31	1.36	6.5	7.41	48%
18/04/2011 22:00:00	11.69	1.16	5.3	5.26	45%
18/04/2011 23:00:00	9.99	0.85	4.5	4.63	46%
					AVERAGE=40%

Appendix D

Minor ion and trace metal results by analyte for all sites.

For full chemistry data in tabular format please refer to files on the attached disc.

Al



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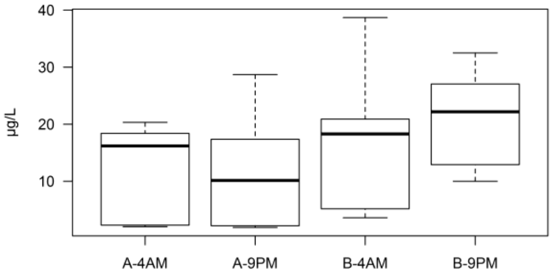

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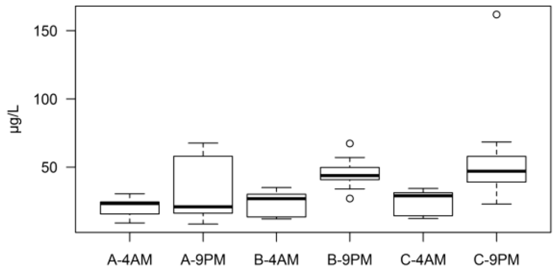

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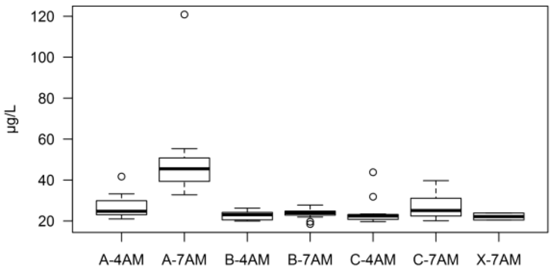

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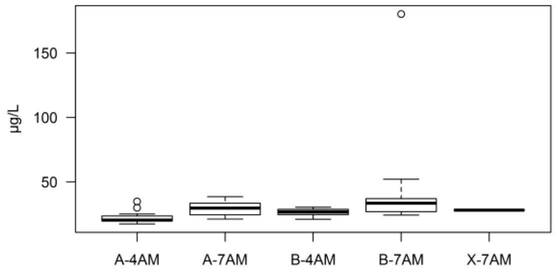

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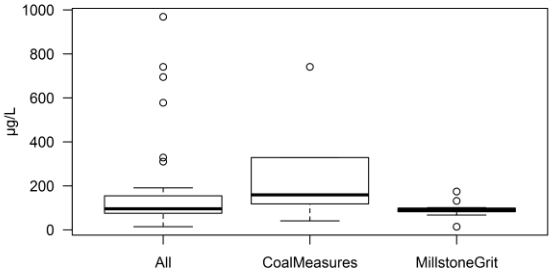
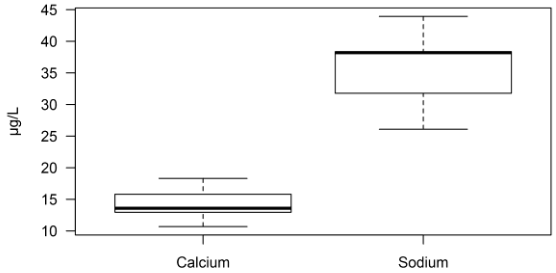
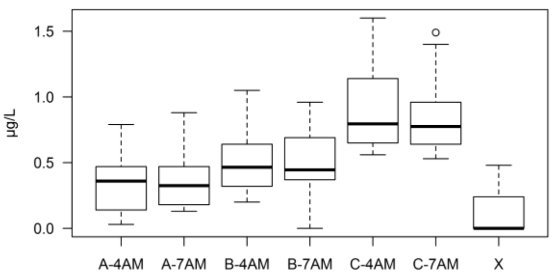


Springwaters



Tapwaters

As



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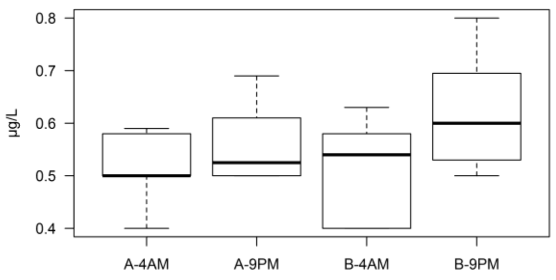

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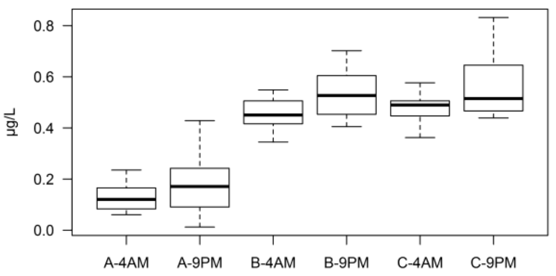

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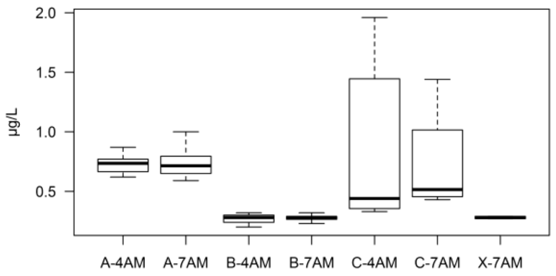

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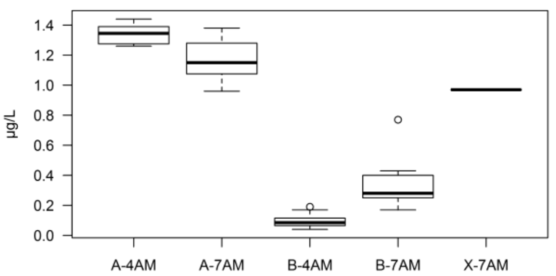

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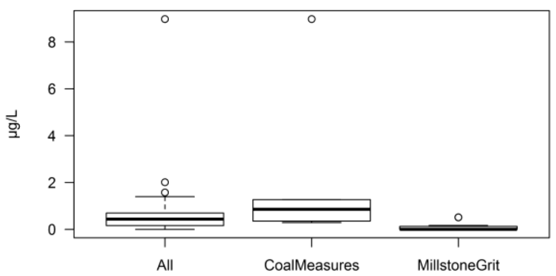
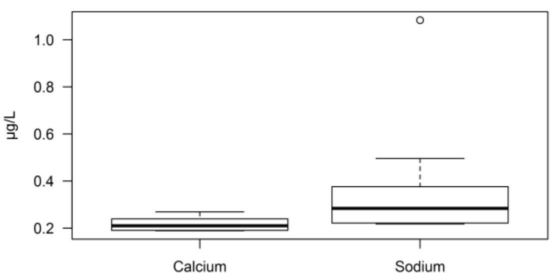


Springwaters



Tapwaters

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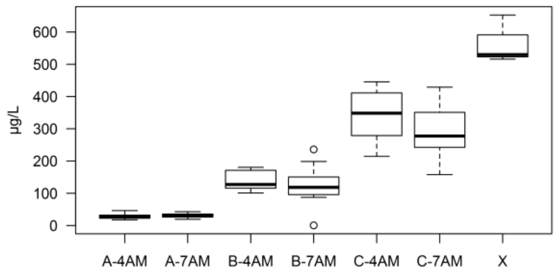

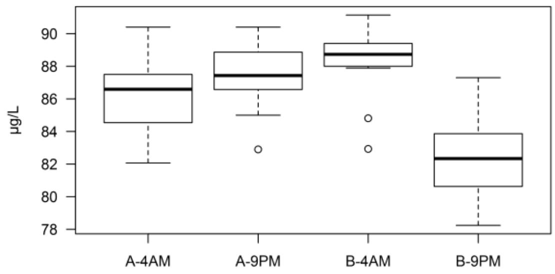

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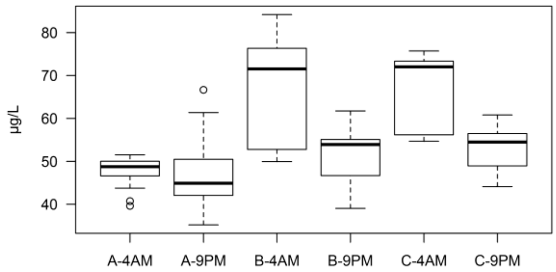

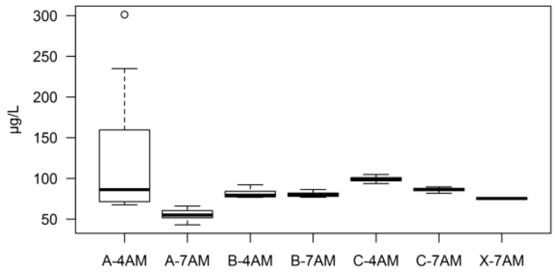

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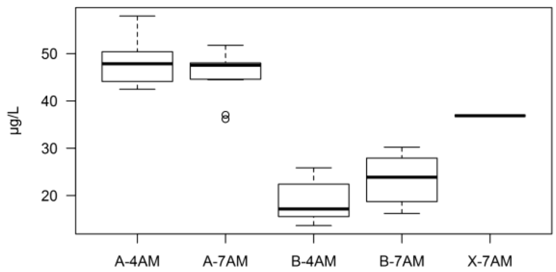
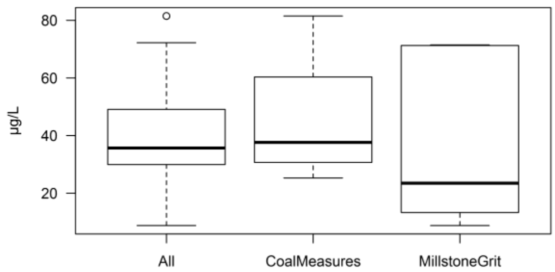
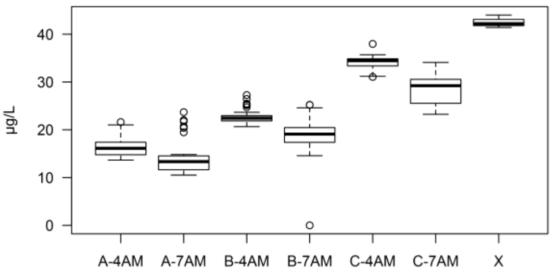


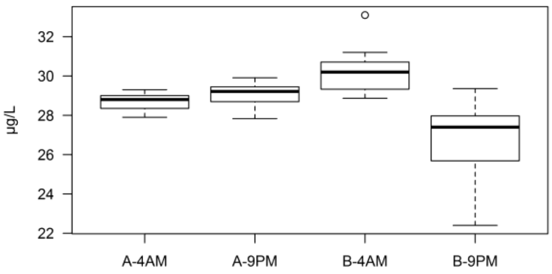


BS

Springwaters

Ba





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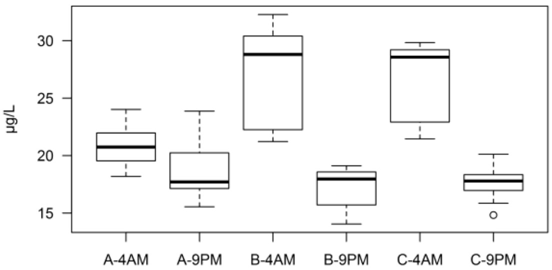

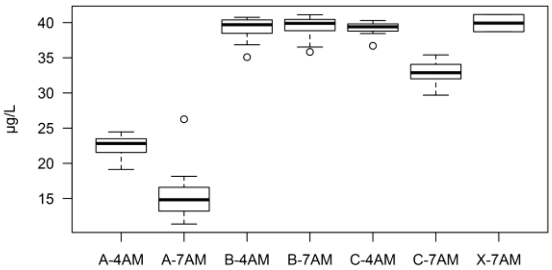

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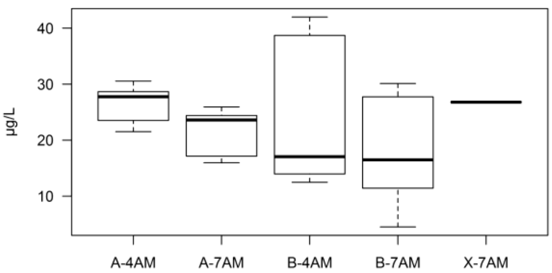
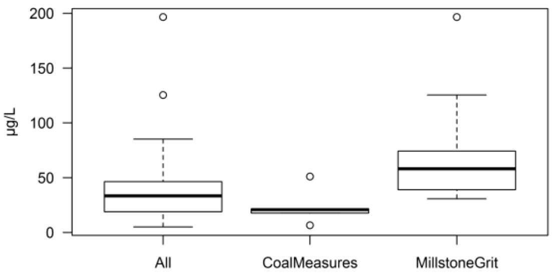
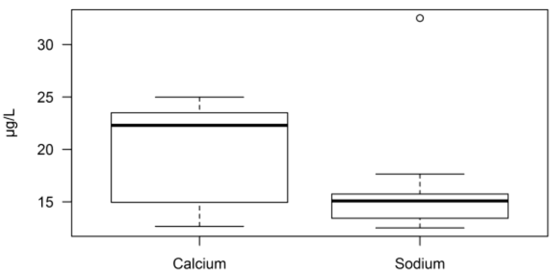




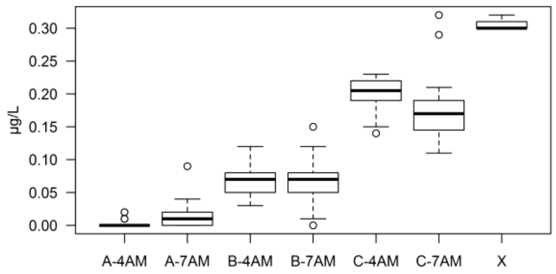
BS

Springwaters



Tapwaters

Co



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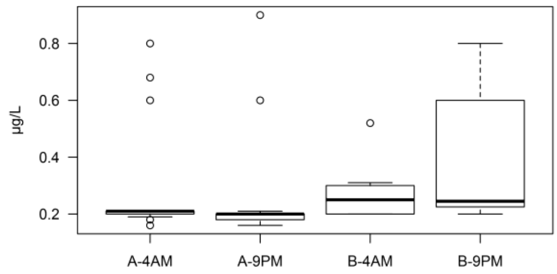

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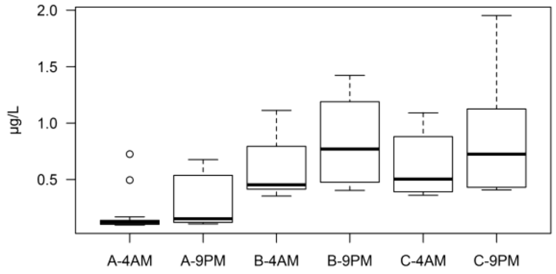

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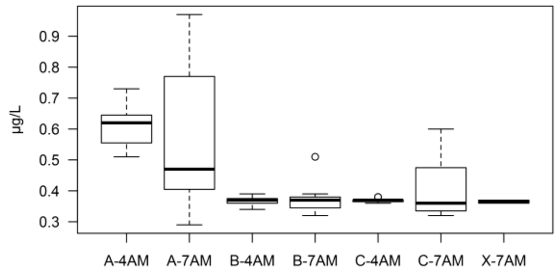

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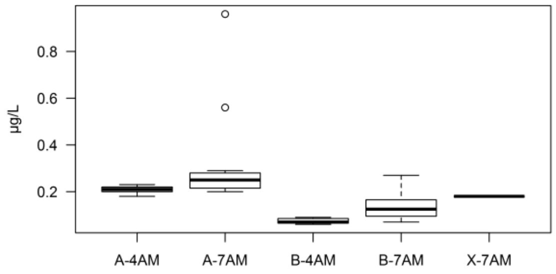

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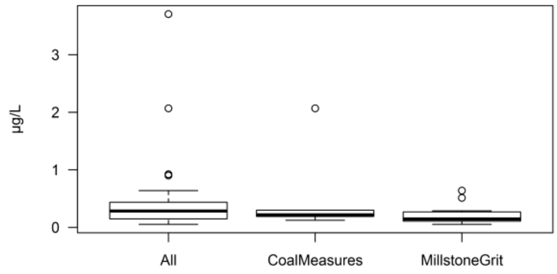

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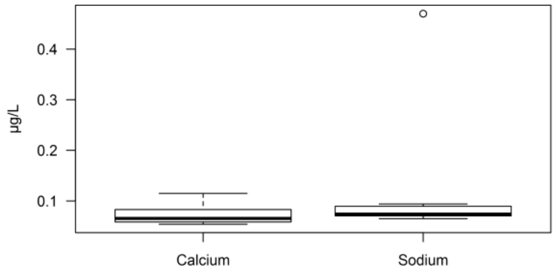

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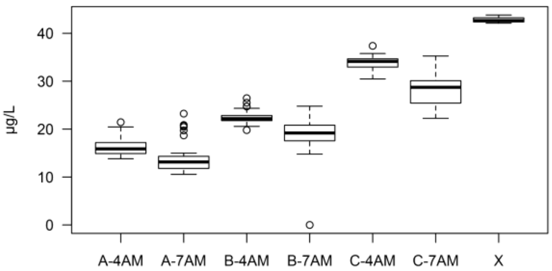
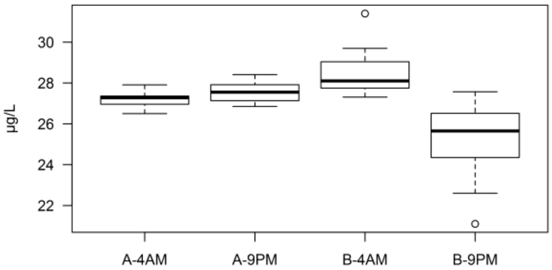
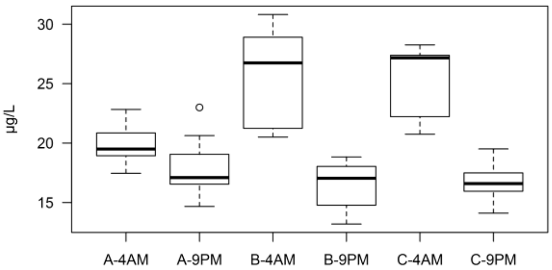
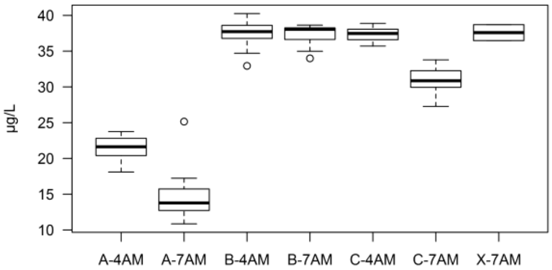
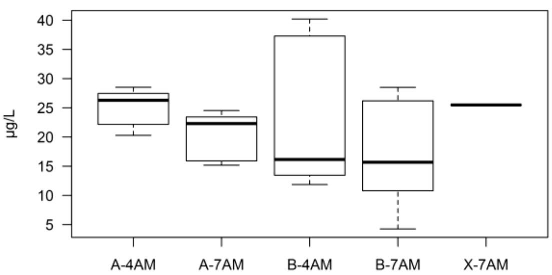
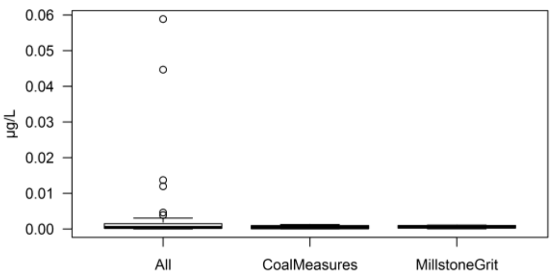
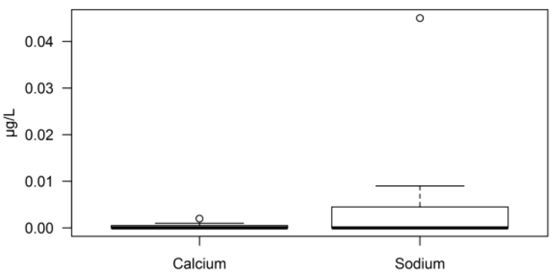
 PW	 HB
 SR	 CV
 BS	 Springwaters
 Tapwaters	

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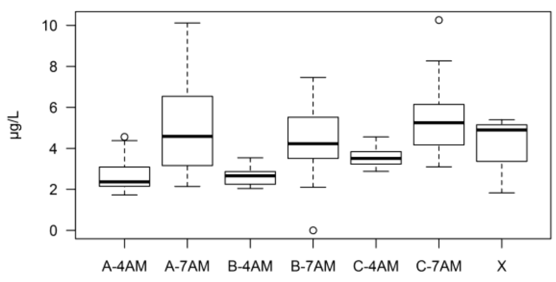

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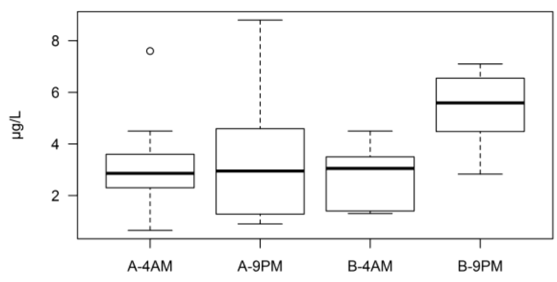

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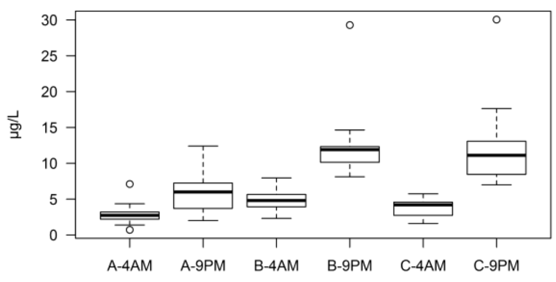

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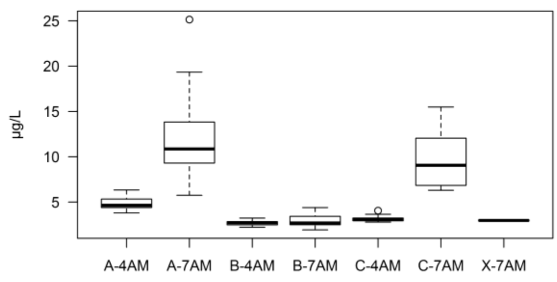

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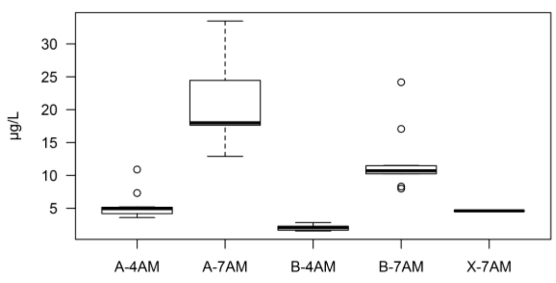

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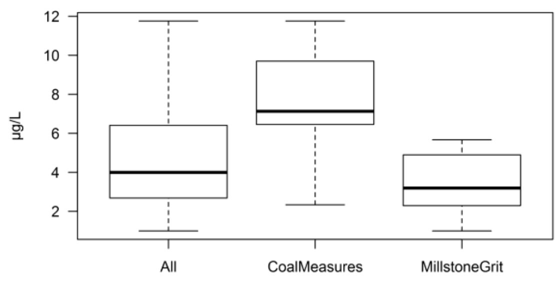

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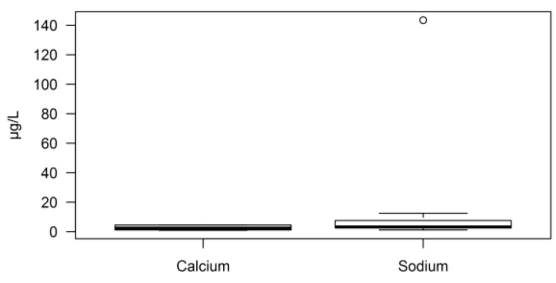

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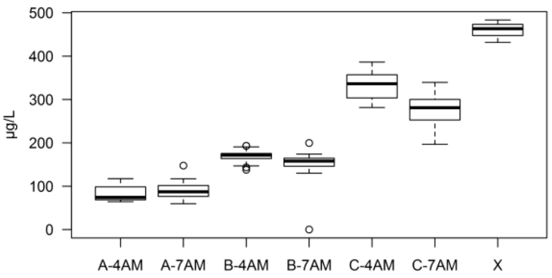

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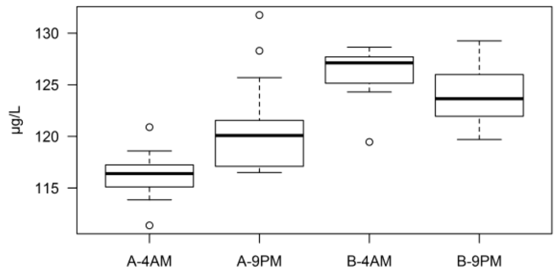

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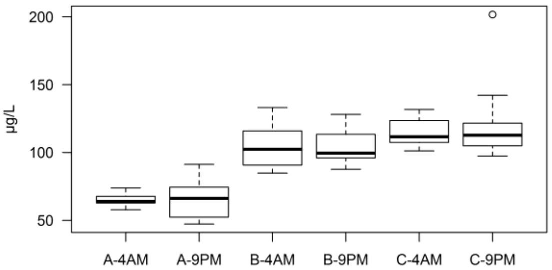

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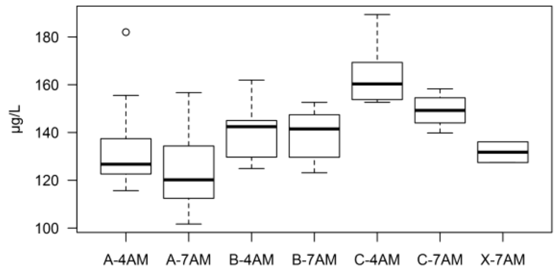

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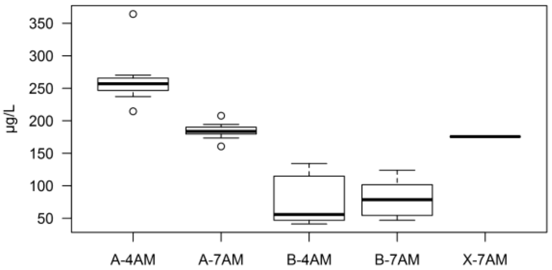

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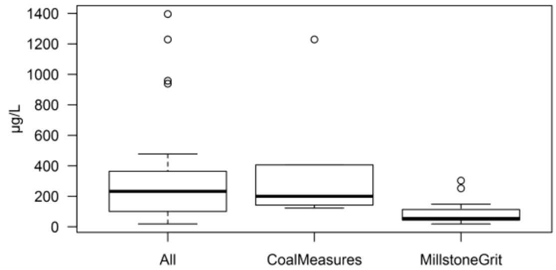

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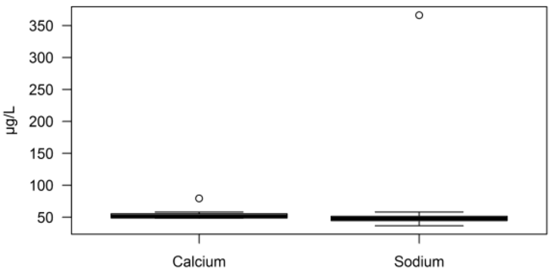

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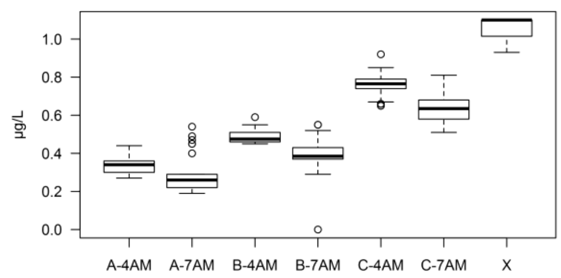

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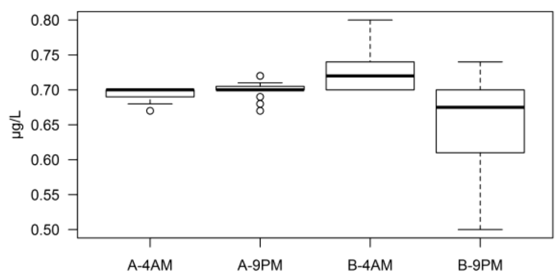

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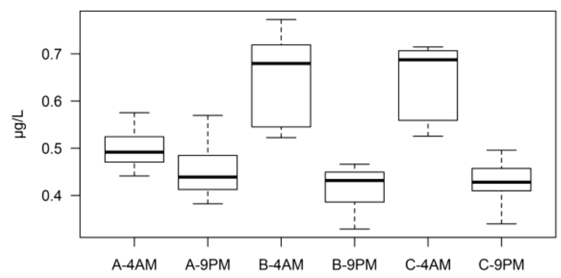

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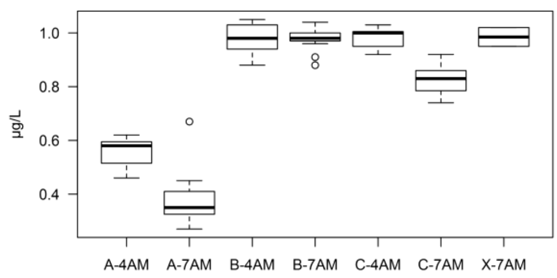

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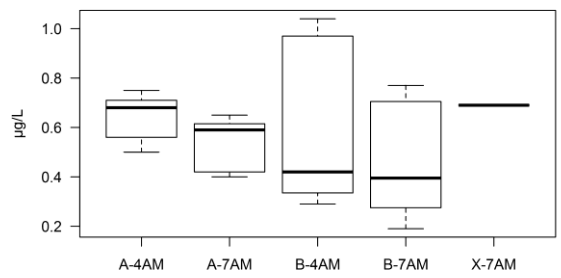

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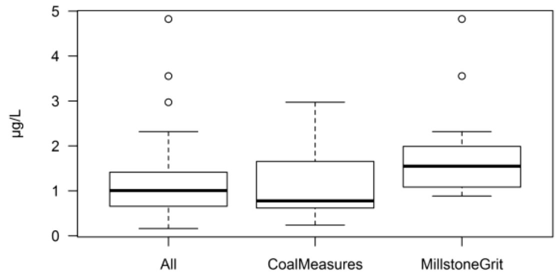

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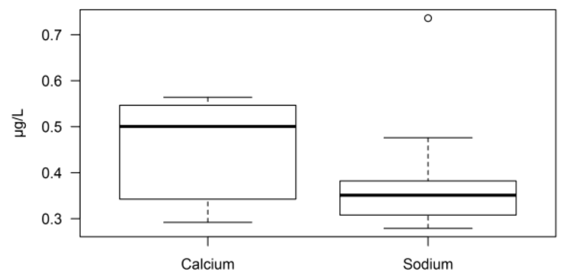

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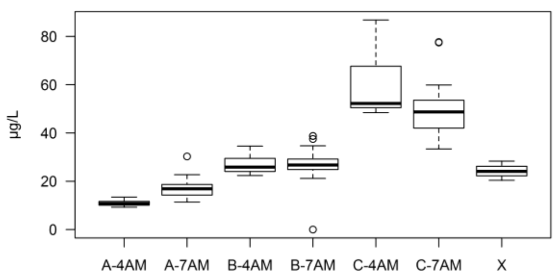

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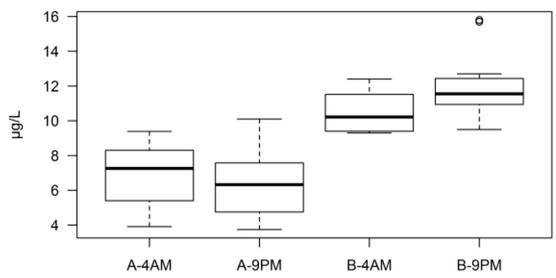

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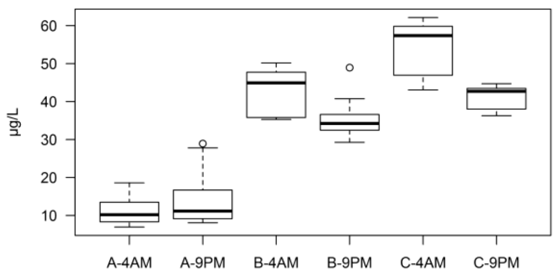

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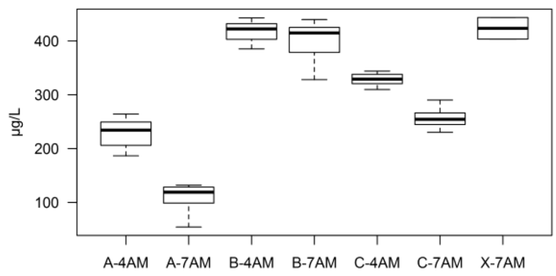

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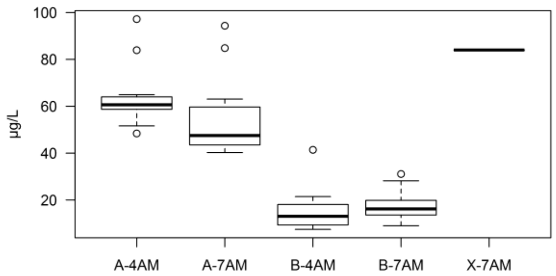

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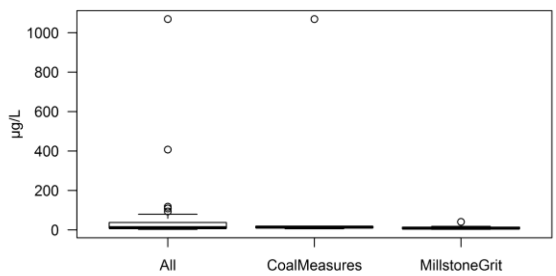

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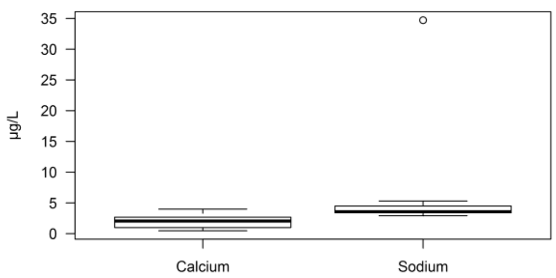

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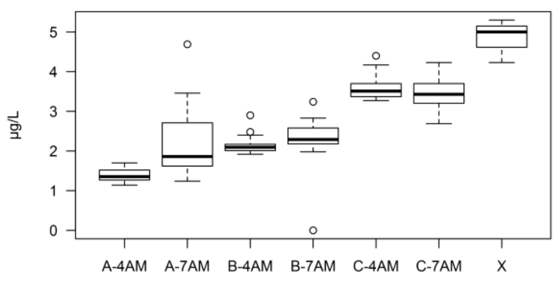

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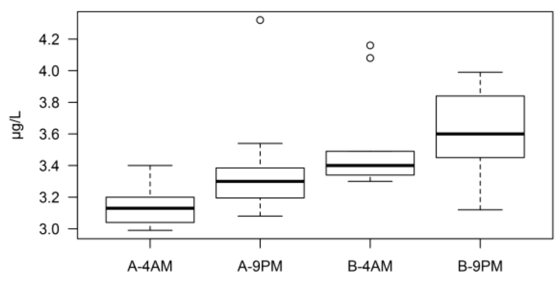

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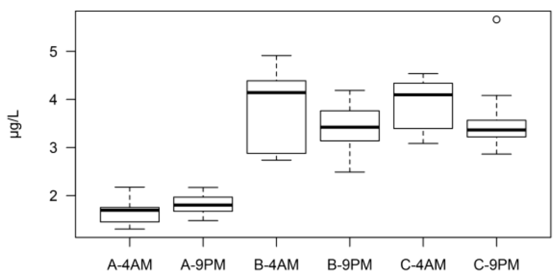

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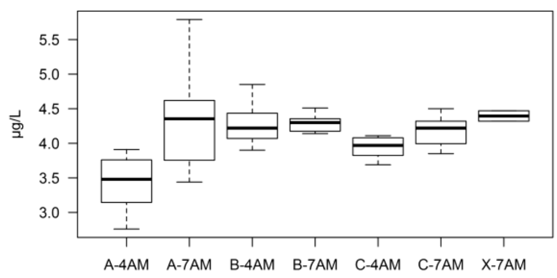

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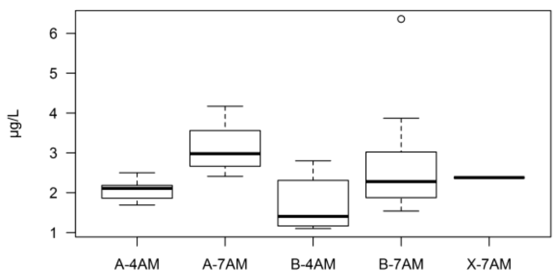

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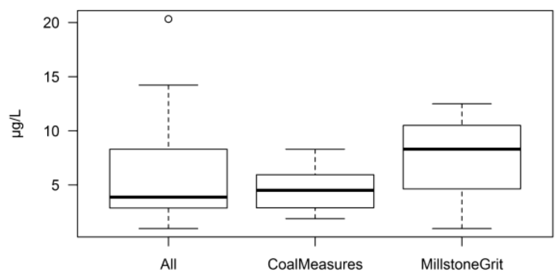

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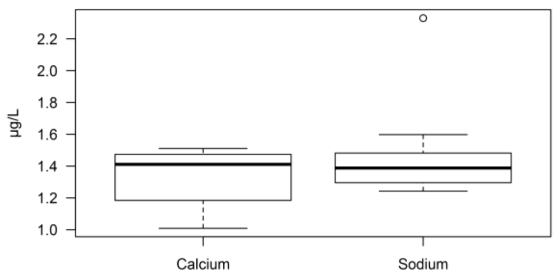

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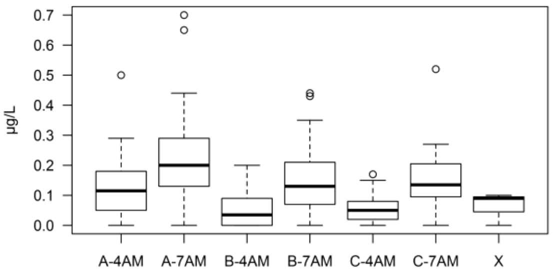

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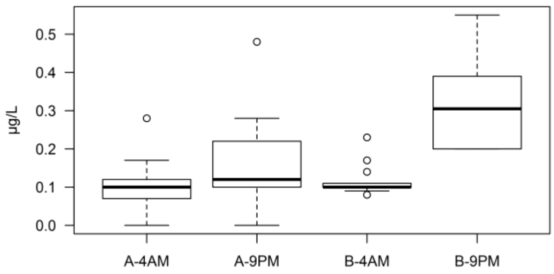

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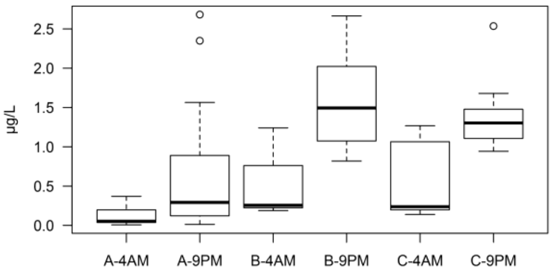

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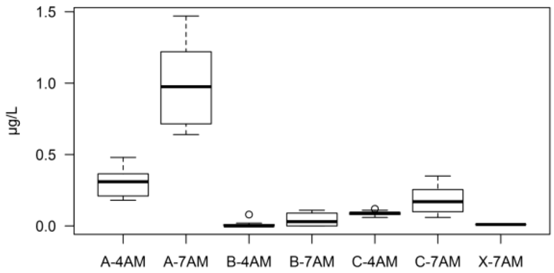

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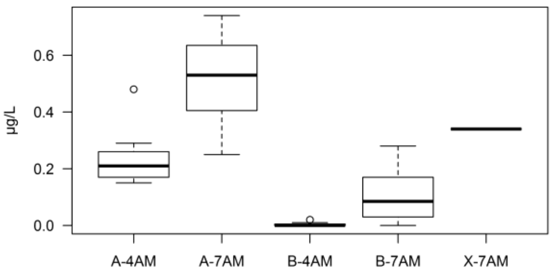

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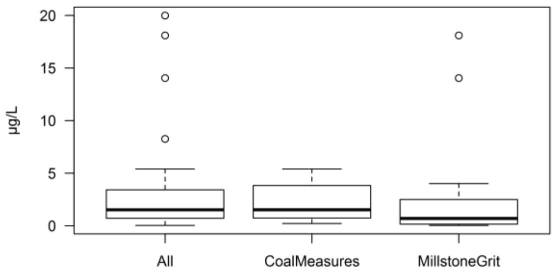

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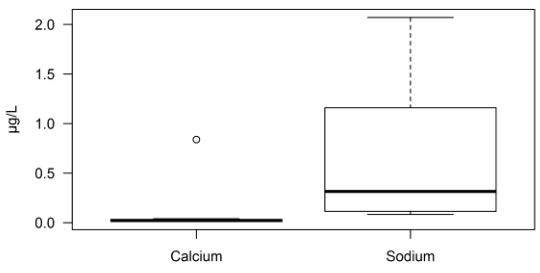

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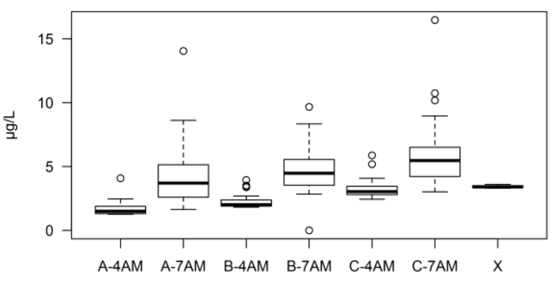

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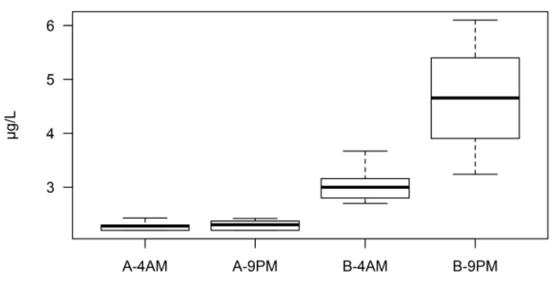

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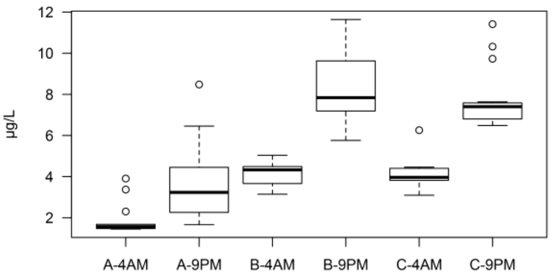

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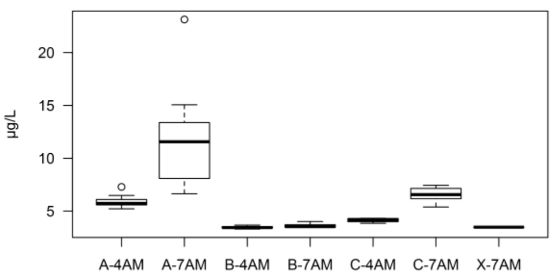

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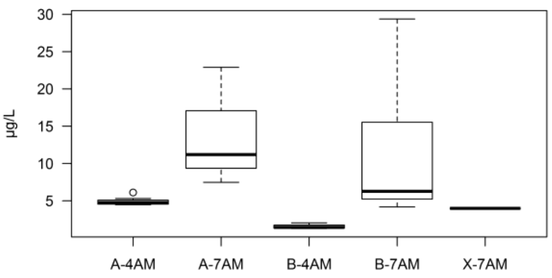

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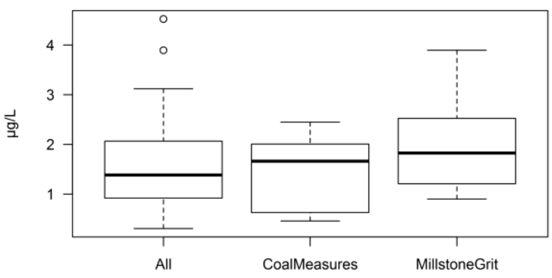

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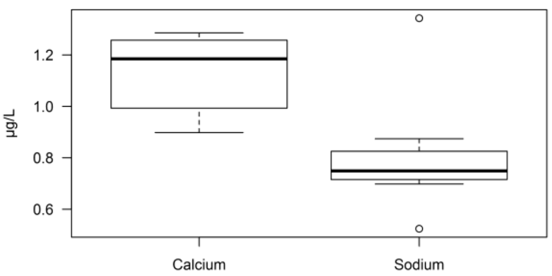

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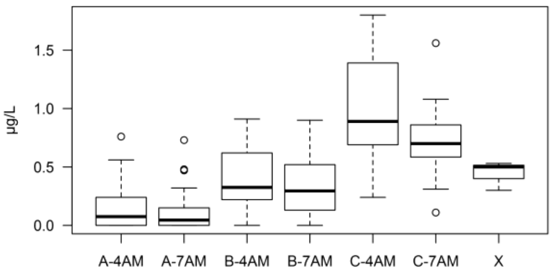

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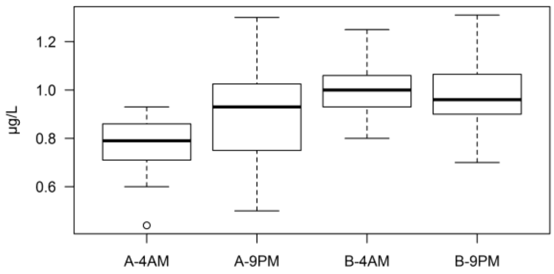

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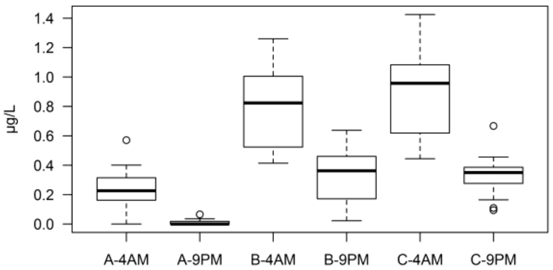

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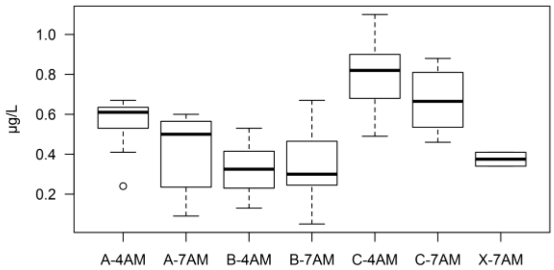

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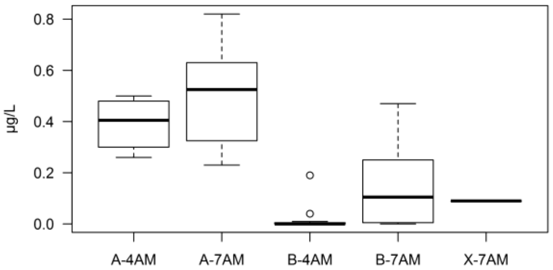

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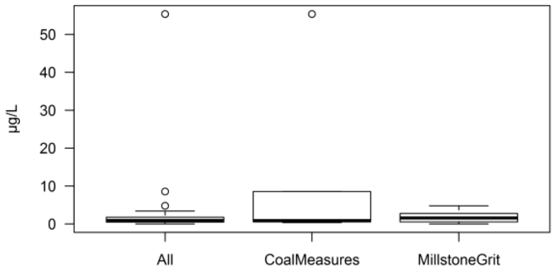

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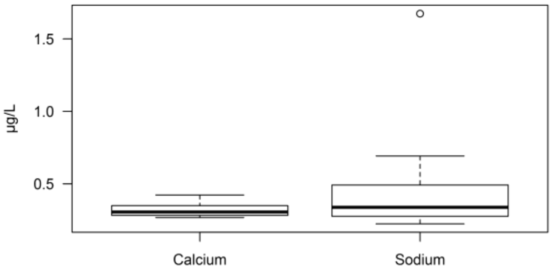

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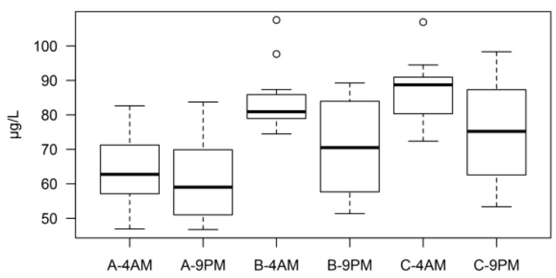

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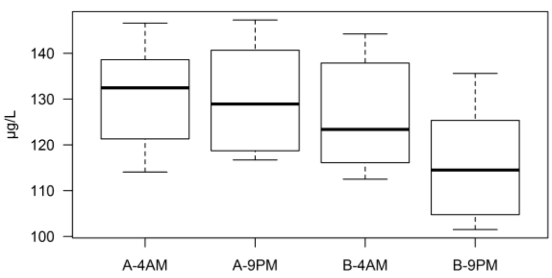

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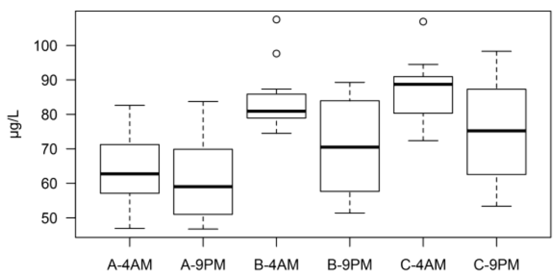

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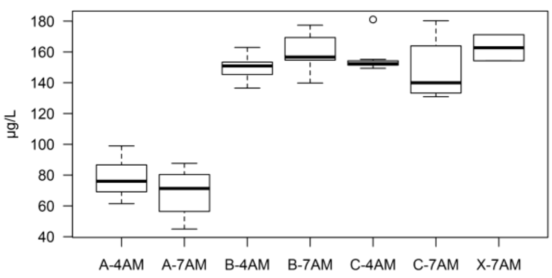

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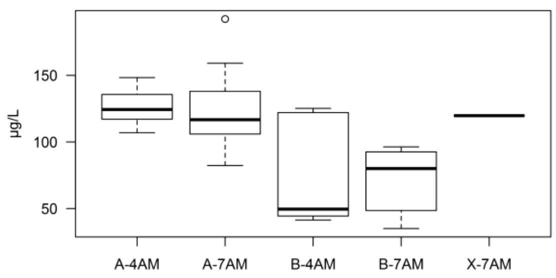

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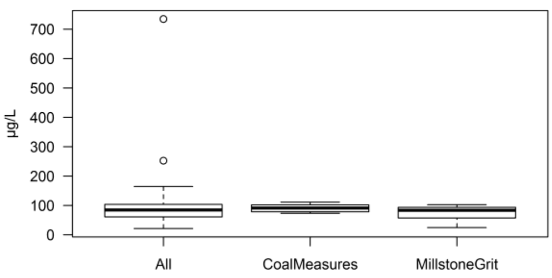

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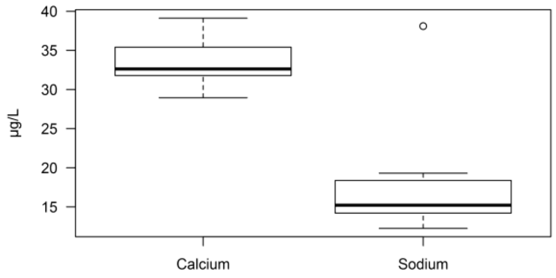

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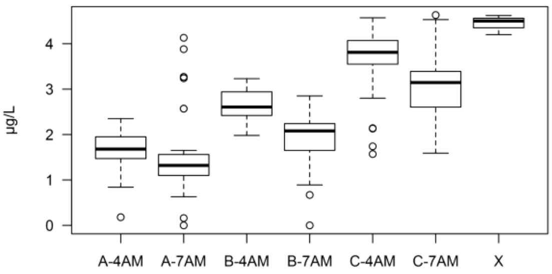

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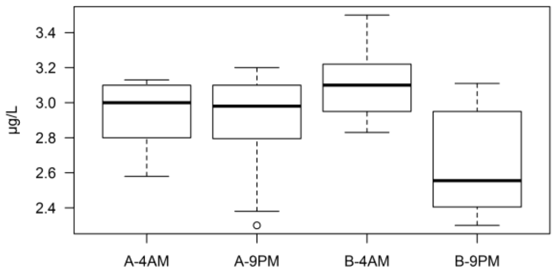

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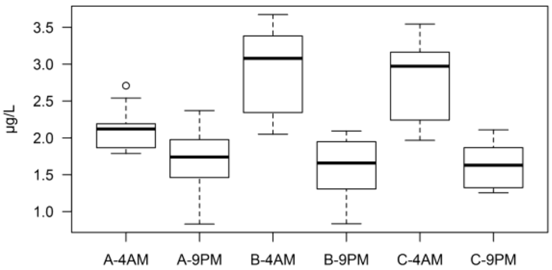

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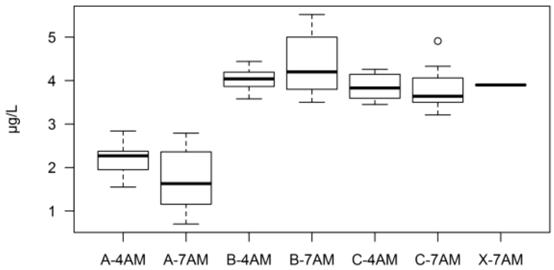

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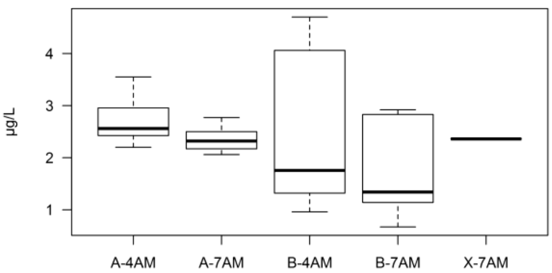

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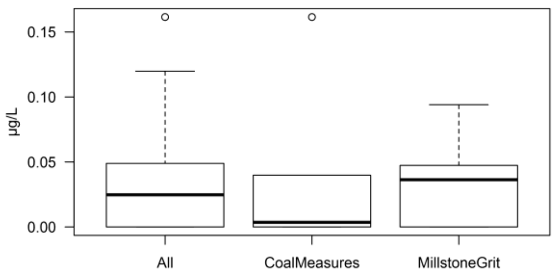

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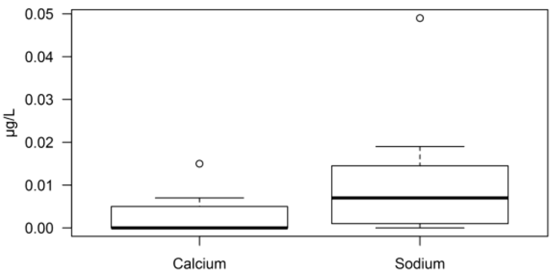

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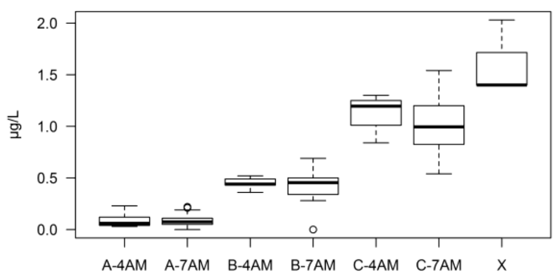

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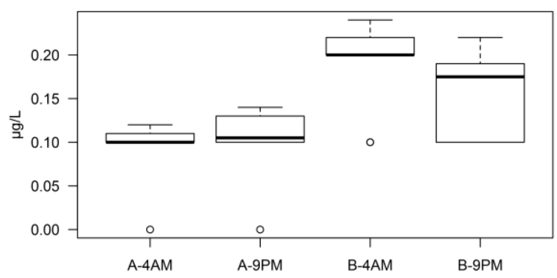

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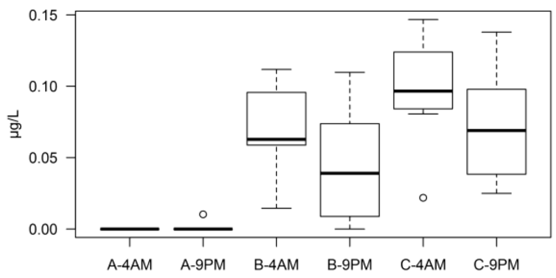

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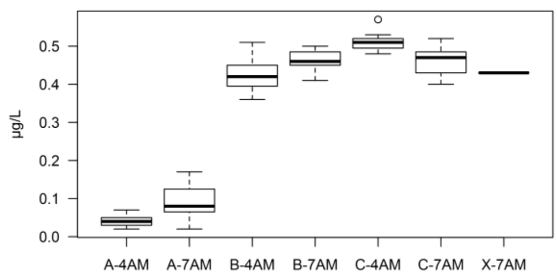

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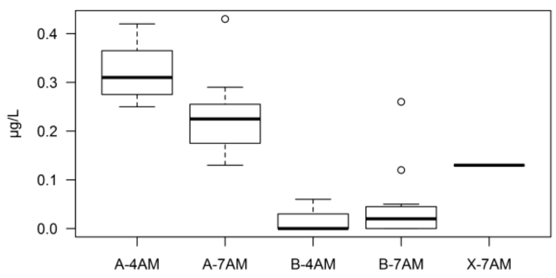

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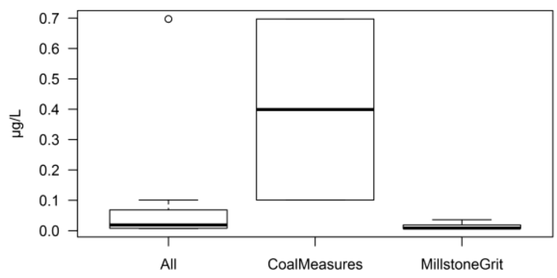

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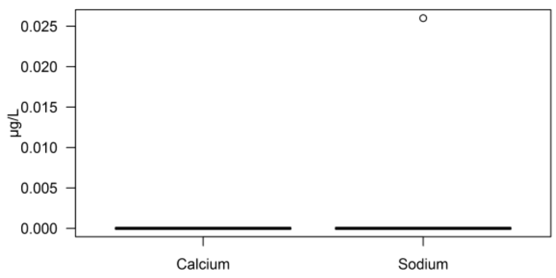

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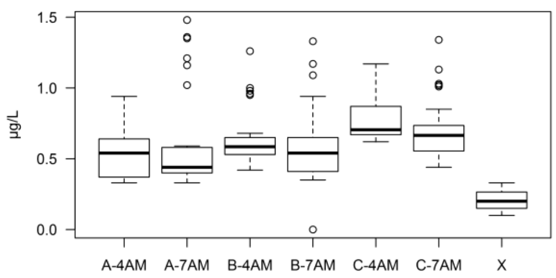

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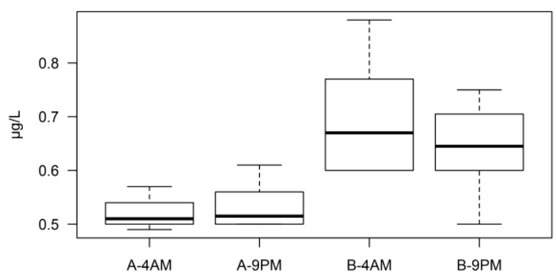

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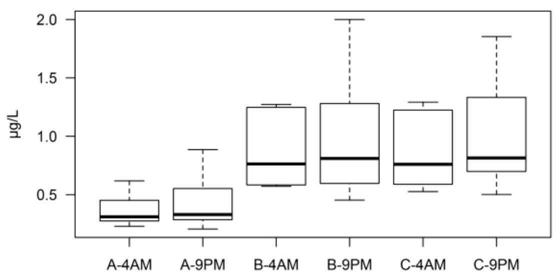

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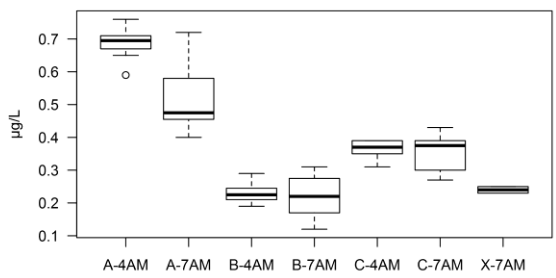

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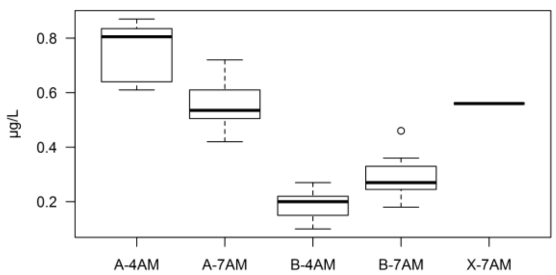

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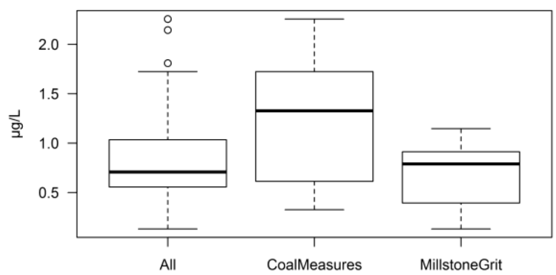

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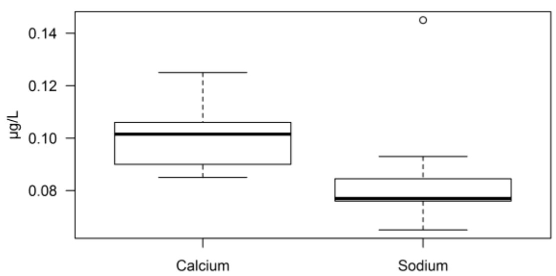

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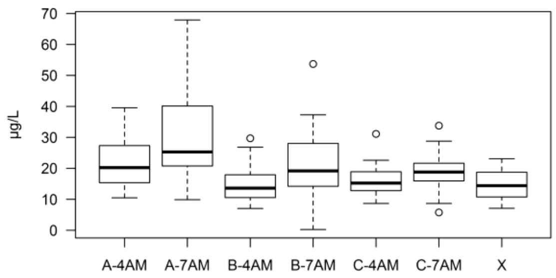

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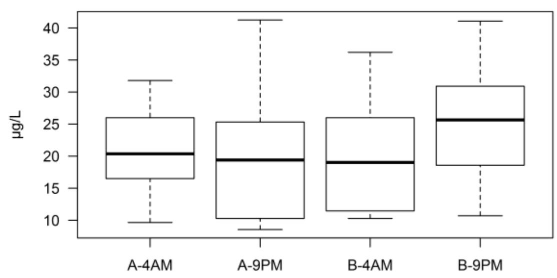

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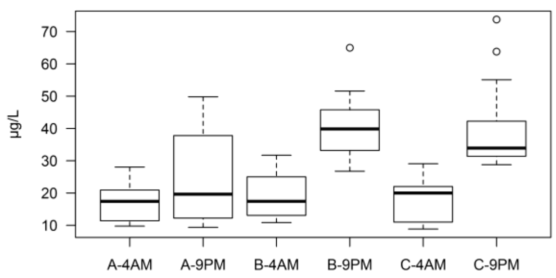

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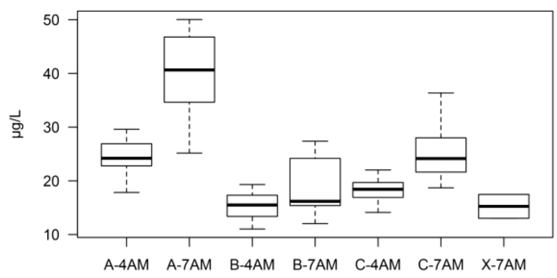

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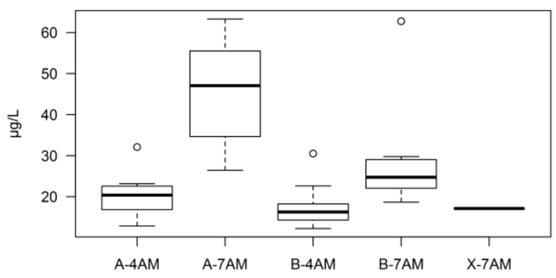

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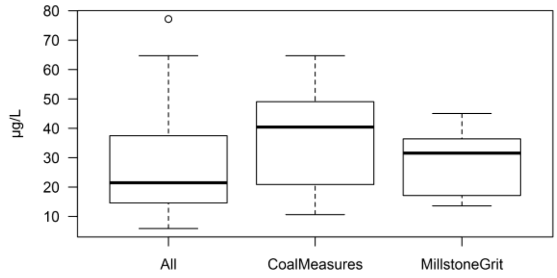

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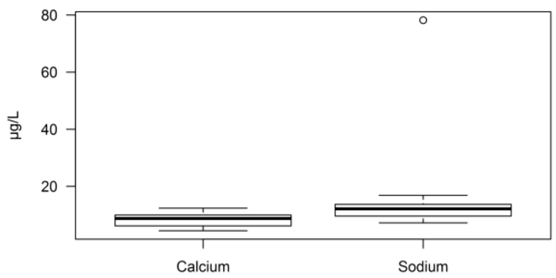

Tapwaters

Appendix E

Expert knowledge questionnaire.

Please refer to files on the attached disc.

Appendix F

Bayesian Belief Network model for Netica software.

Please refer to files on the attached disc.