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Finding lost streams and springs captured in combined sewers: a multiple lines of evidence approach

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Abstract

Some streams and springs have been historically and intentionally captured into combined sewer systems. This is a source of clean baseflow to combined sewers and wastewater treatment works that, unlike groundwater infiltration-inflow through pipe cracks and defective joints, has not been widely considered by the UK water industry. This study presents the first formal methodology, using multiple lines of evidence, to locate lost streams and springs and identify where they have been captured into the combined sewers. In a UK case study, approximately half the total stream length and over 100 natural springs have been apparently lost and could be flowing into the combined sewers. Evidence has demonstrated the suitability of tests to indicate captured flow in sewers, and has confirmed several streams and springs flowing into combined sewers.

Key words stream burial; urban water; culvert; combined sewer; infiltration-inflow.

1 Introduction

Lost streams and springs have been not only culverted beneath urban areas to make space for urban development, but in some cases historically and intentionally connected or converted ("captured") into combined sewer systems (Broadhead et al. 2013). This represents perhaps the severest form of urban stream syndrome with ecological, environmental and social impacts of stream burial, deprivation of clean headwater baseflow to river networks, and implications for flood risk and urban drainage (Everard and Moggridge 2012, Meyer et al. 2007, Walsh et al. 2005). Separation and daylighting of

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captured waters from combined sewers could bring diverse benefits – ecology and water quality, societal amenity and recreation use, flood risk management, and enhanced land value to drive urban regeneration (Broadhead and Lerner 2013, Wild et al. 2011) – and could be influenced by river restoration approaches or by built-environment approaches such as sustainable drainage systems (SuDS) or Green Infrastructure. However, lost captured watercourses, as part of the combined sewer system, may be beyond the immediate reach of the Water Framework Directive (WFD, 2000/60/EC), and are primarily a challenge for the water industry and urban planners. Stream and spring capture is an under-recognised source of clean baseflow to combined sewer networks, in addition to the more widely acknowledged groundwater infiltration-inflow through pipe cracks and defective joints, and presents considerable capital and operational costs for the water industry (Broadhead et al. 2013, Ellis 2001, UKWIR 2012). Reduced pipe capacity increases sewer flood risk and likelihood of combined sewer overflow spills during wet weather, and increases the dry weather flow to the wastewater treatment works (WwTW), with associated pumping, treating and capacity costs.

There is a strong case for water companies to identify and quantify stream and spring capture and evaluate the consequences for the sustainable operation of sewers and WwTWs (Broadhead et al. 2013). Investment to reduce infiltration-inflow by lining or rehabilitating sewers will be undermined if deliberate capture of streams and springs continues. Although studies have attempted to map and quantify rates of stream burial (Bishop et al. 2008, Elmore and Kaushal 2008, Roy et al. 2009), there are few international and no UK examples of a strategic attempt to identify and tackle stream and spring capture into combined sewers. Consequently, no methodology is available to the water industry to identify it.

This paper presents a methodology to indicate where stream and spring capture occurs in combined sewers, and demonstrates its application to a UK case study. We anticipate that this will provide the water industry with a framework to assess where stream and spring capture occurs in combined sewer networks. By raising awareness of captured streams and springs, we hope to prompt debate about future management of this urban water, including its separation from the sewers and restoration of functioning urban watercourses for environmental, social and economic benefit. We address the following questions:

- What evidence is available to locate lost streams and springs and indicate capture, and how should this be applied?
- How many streams and springs have been lost in a typical catchment?
- How many streams and springs have been captured into the combined sewer system in a typical catchment?

2 Method

2.1 Capture indication methodology

Some watercourses may be directly intercepted by a combined sewer so that a discrete inflow can be observed or checked with connectivity tests, some have been converted into combined sewers from their source and have no known or easily identifiable point of entry to the sewer. There are numerous direct and indirect methods available to identify the presence of captured flow within a combined sewer, some of which have been used in identifying infiltration-inflow (UKWIR 2012). However, because they first require suitable inspection locations to be identified, they may be inappropriate for a pro-active network-wide assessment.

Even determining the original locations of lost streams and springs presents a considerable challenge. Modern maps rarely include all culverts, and although historical maps can show former streams and springs, the detail depends on the available spatial and temporal coverage at different map scales and types. Delineating stream networks from topographic digital elevation model (DEM) data is a widely used technique using extensions such as HydroTools in ArcGIS software (Tarboton et al. 1991). Studies have used this to assess stream burial in North America (Elmore and Kaushal 2008, Roy et al. 2009). Topographic flowpath modelling is based solely on topography, with no consideration of the physical or hydrological processes that influence stream networks. Its output is determined by the accuracy of the topographic data; modern DEMs will be influenced by made-ground in urban areas – accurate historical contour data are rarely available.

We consider three stages of a capture indication methodology:

1. *locating* lost streams and springs;
2. *indicating* where they may be captured into combined sewers;

3. *verification* options available to confirm or rule out suspected capture.

Data for each line of evidence were gathered for the case study and applied in a Geographical Information System (GIS).

2.2 Study catchment

Sheffield is a typical city in northern England, bordered by hills and situated at the confluences of the rivers Sheaf, Loxley, Rivelin, Porter and Don. The city expanded during the industrial revolution and early 20th century; subsequently many watercourses were modified or culverted. Sheffield is served by predominantly combined sewers, but separate sewers are found in some developments and numerous surface water pipes are found within otherwise combined sewer areas. Approximately 285,000 m^3/d of wastewater drains to Blackburn Meadows WwTW near Rotherham (Green 2002), and there is considerable operational expenditure 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 daylight culverted watercourses for flood risk and urban regeneration benefits (Creative Sheffield 2008, Sheffield City Council 2010). A 89 km^2 search area was delineated, including the city centre and some older suburbs, and the majority of the River Sheaf and Porter Brook catchments.

2.3 Data sources and application of lines of evidence

Multiple lines of desk-based evidence for locating lost streams and springs were compiled for the study catchment in GIS (**Table 1**). For the topographic flowpath modelling, the flow accumulation threshold represents the area upstream of a delineated stream origin (channel initiation point), and was calibrated against 61 training points of observed stream origins from historical maps and modern maps. It is more favourable to overestimate stream length at this stage to avoid prematurely ruling out potential lost streams, as studies have highlighted that many urban headwaters have been piped (Roy et al. 2009). Seven flow accumulation thresholds were tested, measuring the error as average distance between the training point and modelled stream origins, with a positive distance reflecting underestimation and negative distance reflecting overestimation (**Figure 1**). A 400 m^2 flow accumulation threshold was chosen to cautiously overestimate modelled stream length (mean -110 m; σ=260; n=61). The large standard deviations reflect uncertainty in both the technique's underlying assumptions and difficulty in precisely locating known stream origins as training points, supporting the need to be conservative.

Information for indicating and verifying stream and spring capture included sewer network and flow survey data provided by Yorkshire Water, as well as a sewer sampling programme that applied a major and minor ion water typing method to detect mixing of captured waters and wastewater in combined sewers (**Table 2**).

3 Results and analysis

3.1 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 2A**). Historical maps, predominantly prior to 1900, show 140 km of open watercourse, including extended lengths of headwater tributaries as well as smaller watercourses completely lost from modern records (**Figure 2B**).

Topographic flowpath modelling generated a total predicted stream length of 330 km in the search area (**Figure 2C**). This is likely to be an overestimation, reflecting the chosen flow accumulation threshold and a feathering effect of multiple flowpath lines in flatter areas. 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. The remaining 25% are at distances of up to 250 m, typically in floodplain areas where flat topography limits horizontal accuracy of channel location. Acknowledging these sources of potential error, topographic flowpath modelling provides a suitable first-pass analysis of likely stream locations; it is relatively quick and allows targeting of more time-consuming historical map searches and other lines of evidence.

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

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

The lines of evidence were mapped and visually combined to digitise a best available estimate of 187 km of original stream network in Sheffield (**Figure 3**). This is an estimated 64 km of lost watercourse missing from the search area, unrecorded as watercourse or culvert, and therefore may be captured. This equates to 52% loss or total burial of stream length in the search area.

3.2 Indicating stream and spring capture

Visual comparison of the results against sewer network maps showed several lost watercourses replaced by surface water sewers flowing to a downstream river (though potential daylighting candidates for capacity improvements, they are not strictly-speaking captured). In at least thirteen cases, these surface water sewers discharge to combined sewers, indicating capture by interception (**Figure 3**). In other cases, capture cannot be confidently indicated from sewer network maps; many lost streams or springs have no obvious nearby 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 27 sewer flow monitors showed significantly higher baseflow in sites where lost streams and springs may be captured by combined sewers compared to locations of no lost streams or springs (Student's t-test, $t=4.19$, $df=22$, $p=0.00038$). 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.

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. At this one location, it was possible to confirm by site visit that springs were piped into a garden pond which overflows to a combined sewer.

A water typing chemistry study using major and minor ions and visual verification was applied to five sites determined by the capture indication methodology (Broadhead et al. in preparation) (**Figure 3**). The method successfully differentiated water types of captured streams and springs from wastewater at sites 1, 2 and 4, where culverted or open watercourses discharge directly into combined sewers, detecting captured water in the diurnal wastewater chemistry. Geological heterogeneity in this catchment made estimation of captured stream and spring chemistry difficult; the water typing technique was inconclusive at site 3 where a watercourse has been converted into a combined sewer at source and no captured water could be individually sampled (though a spring-fed pond was observed to overflow to the combined sewer). At site 5, sewer network maps and topography suggest that nearby lost streams would not flow into the combined sewers sampled; the water typing was inconclusive, possibly reflecting infiltration-inflow in the sewer.

4 Discussion

4.1 Reviewing the lines of evidence: towards a procedure

The results of locating lost streams and springs and indicating where they have been captured into combined sewers suggest that no single test or evidence can easily or infallibly identify capture. A multiple lines of evidence approach is therefore required. For users in the water industry, 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, and the reliability or confidence of each test. Drawing on the literature and the application to the case study, each line of evidence was qualitatively assessed for characteristics considered to be important for future application. The results presented in **Table 3** have been used to develop a procedural methodology flowchart (**Figure 4**).

First, desk-based evidence in GIS should be used to determine the known stream network, then locate lost water features. Given the good accuracy of the topographic flowpath modelling achieved in this study, this is recommended 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. Known open or culverted streams and springs flowing to the river network can be eliminated from enquiry. Each additional line of evidence corroborating the possibility that a former stream or spring is no longer connected to the modern river network strengthens the likelihood that it is lost and a candidate for capture; reliance on a single test is unlikely to provide adequate confidence.

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 be verified by commissioning a site investigation to determine the connectivity; it is possible that the sewer network data are incorrect and should be revised.

Sewer network maps can also indicate the conversion of lost streams and springs into combined sewers. Where replaced by surface water sewers flowing to a downstream river, capture can be ruled out. Where there are no alternative flow routes other than combined sewers, 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. 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. 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 from infiltration-inflow or mains water leakage, directly observed as leakage through pipe cracks and defective joints using CCTV and techniques outlined elsewhere (UKWIR 2012).

4.2 Implications for the water industry

Application of the capture indication methodology has identified many lost streams and springs in a typical urban catchment. While some 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 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 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 published methodology to indicate where lost streams and springs are captured into combined sewers. Despite some examples of managing stream and spring capture in Zurich or Pittsburgh, none have detailed a methodology, making comparison difficult (Broadhead et al. 2013). 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. Detailed quantification of captured flow contribution to the combined sewer network has not been possible at this stage; however, fieldwork has suggested dry weather flowrates very approximately in the range of 0.5–2 L/s and 3–4 L/s at sites 1 and 4, respectively (Broadhead et al. in preparation). Further application of the lines of evidence, including hydrological surveys to check whether springs have dewatered and fieldwork to estimate the flow rates of the water prior to capture or indirectly from sewer flow data would enable a thorough quantification of the number of captured streams and springs in this catchment, the volume of clean baseflow they contribute, and whether this risks capacity-related problems such as sewer flooding, surface water flooding or combined sewer overflow 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 and elsewhere. For a discussion of the typical quantities and quantification methods available from the literature, see Broadhead et al. (2013).

5 Conclusion

1. A capture indication methodology (**Figure 4**) can locate lost streams and springs and indicate where they may be captured into the combined sewer system.
2. Combining multiple lines of evidence is recommended to address uncertainty. 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.
3. In a UK catchment, we show that less than 25% of the total stream length is culverted, but over 50% of the stream length and over 100 springs are buried or lost completely. Several sites where streams and springs flow into combined sewers to the WwTW were confirmed.
4. Stream and spring capture is worthy of further attention by the water industry to apply the methodology elsewhere, examine the full costs and impacts, and explore opportunities for sustainable management.

6 Acknowledgements

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7 References

Addy, S.O. (1888) *A Glossary of Words Used in the Neighbourhood of Sheffield*, English Dialect Society: London.

Banks, D. (1997) 'Hydrogeochemistry of Millstone Grit and Coal Measures groundwaters, south Yorkshire and north Derbyshire, UK'. *Quarterly Journal of Engineering Geology and Hydrogeology* 30(3), 237-256.

Banks, D., Burke, S.P. and Gray, C.G. (1997) 'Hydrogeochemistry of coal mine drainage and other ferruginous waters in north Derbyshire and south Yorkshire, UK'. *Quarterly Journal of Engineering Geology and Hydrogeology* 30(3), 257-280.

Bishop, K., Buffam, I., Erlandsson, M., Fölster, J., Laudon, H., Seibert, J. and Temnerud, J. (2008) 'Aqua Incognita: The unknown headwaters'. *Hydrological Processes* 22(8), 1239-1242.

Blackwell, J. (1828) *The Sheffied Directory and Guide Containing a History of The Town*, Blackwell: Sheffield.

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.

Broadhead, A.T., Horn, R. and Lerner, D.N. (in preparation) 'Water typing for detection of captured streams and springs in combined sewers'.

Broadhead, A.T. and Lerner, D.N. (2013) 'www.daylighting.org.uk: case study website supporting research into daylighting urban rivers'. *Hydrological Processes* 27(12), 1840-1842.

Creative Sheffield (2008) *Sheffield City Centre Masterplan*, Sheffield City Council, Sheffield.

Crossley, D. (ed) (1989) *Water Power on the Sheffield Rivers*, Sheffield Trades History Society: Sheffield.

Davy, S.R. (1970) *Where t'watter runs o'er t'weir: A look at Sheffield's Watermills*, Unpublished: Sheffield.

Duncan, S. (2011) *Urban Exploration: Rivers and Cities in Northern England* (WWW), UnderCity: New York. (http://undercitynorthernenglandstory.blogspot.com/; 08/01/2013).

Ellis, J.B. (2001) 'Sewer infiltration/exfiltration and interactions with sewer flows and groundwater quality'. *Interurba II*, Lisbon, Portugal, 19-22 February 2001. (http://apuss.insa-lyon.fr/c001_sewer_infiltration_exfiltration_and_interactions_with_sewer_flows_and_groudwater_quality.pdf; 08/01/2013).

Elmore, A.J. and Kaushal, S.S. (2008) 'Disappearing Headwaters: Patterns of Stream Burial Due to Urbanization'. *Frontiers in Ecology and the Environment* 6(6), 308-312.

Everard, M. and Moggridge, H.L. (2012) 'Rediscovering the value of urban rivers'. *Urban Ecosystems* 15(2), 293-314.

Galster, J.C. (2012) 'Removing streams from the landscape: counting the buried stream beneath urban landscapes'. *GSA Annual Meeting: Geomorphology of the Anthropocene: The Surficial Legacy of Past and Present Human Activities*, Charlotte Convention Center, 4 November 2012. (https://gsa.confex.com/gsa/2012AM/finalprogram/abstract_208065.htm; 22/04/2013).

Green, J. (2002) *The relationship between the water cycle and the city*, The University of Sheffield, Sheffield.

Hall, T.W. (1922) *Sheffield and its environs 13th to the 17th century*, J.W. Northend: Sheffield.

Hey, D. (2010) *A History of Sheffield*, Carnegie Publishing: Lancaster.

Holland, J. (1824) *Picture of Sheffield or An Historical and Descriptive View of the Town of Sheffield*, George Ride: Sheffield.

Ibrahim, T., Thornton, S. and Wainwright, J. (2010) 'Interplay of geomorphic and hydrogeologic features at reach- and channel unit-scales on riverbed hydrology and hydrochemistry: a conceptual model in the Lower Coal Measures, South Yorkshire, UK'. *Hydrogeology Journal* 18(6), 1391-1411.

Jones, H.K., Morris, B.L., Cheney, C.S., Brewerton, L.J., Merrin, P.D., Lewis, M.A., MacDonald, A.M., Coleby, L.M., Talbot, J.C., Mckenzie, A.A., Bird, M.J., Cunningham, J.E. and Robinson, V. (2000) *The physical properties of minor aquifers in England and Wales (British Geological Survey): WD/00/004 EA R&D Publication 68*, Bristol.

Leader, R.E. (1875) *Reminiscences of old Sheffield, its streets and its people*, Leader and Sons: Sheffield.

Leader, R.E. (1901) *Sheffield in the Eighteenth Century*, Sheffield Independent Press: Sheffield.

Meyer, J.L., Strayer, D.L., Wallace, J.B., Eggert, S.L., Helfman, G.S. and Leonard, N.E. (2007) 'The Contribution of Headwater Streams to Biodiversity in River Networks'. *Journal of the American Water Resources Association* 43(1), 86-103.

Olive, M. (2006) *A Short History of Sheffield*, Sheffield Libraries Archives and Information: Sheffield.

Roy, A.H., Dybas, A.L., Fritz, K.M. and Lubbers, H.R. (2009) 'Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area'. *Journal Of The North American Benthological Society* 28(4), 911-928.

Sheffield City Council (2010) *Masterplan: Crookes Valley Park, Ponderosa, Philadelphia Gardens*, Sheffield City Council: Sheffield.

Stainton, J.H. (1924) *The Making of Sheffield*, E. Weston and Sons: Sheffield.

Tarboton, D.G., Bras, R.F. and Rodriquez-Iturbe, I. (1991) 'On the extraction of channel networks from digital elevation data'. *Hydrological Processes* 5(1), 81-100.

Taylor, J. (ed) (1879) *The Illustrated Guide to Sheffield and The Surrounding District*, Pawson and Brailsford: Sheffield.

The London Gazette (1901) 'Sheffield Corporation Act 1900'. *The London Gazette* 27301(Tuesday 2nd April), 2281-2286.

UKWIR (2012) *Strategic Infiltration (12/SW/01/1)*, UK Water Industry Research: London.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M. and Morgan II, R.P. (2005) 'The urban stream syndrome: Current knowledge and the search for a cure'. *Journal Of The North American Benthological Society* 24(3), 706-723.

Walton, M. (2011) *Street Names Study Guide*, Sheffield Libraries Archives and Information: Sheffield.

White, W. (1837) *History, gazetteer and directory of the West Riding of Yorkshire*, Leader and Sons: Sheffield.

Wild, T.C., Bernet, J.F., Westling, E.L. and Lerner, D.N. (2011) 'Deculverting: reviewing the evidence on the ‘daylighting’ and restoration of culverted rivers'. *Water and Environment Journal* 25(3), 412-421.

Woolhouse, J. (1832) *Description of the town of Sheffield: in my remembrance wrote in the year 1832 at the time the Cholera was raging in Sheffield*, The Ford: Sheffield.

Tables

Table 1 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 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: • www.sheffieldforum.co.uk • www.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 2011, Hey 2010, Olive 2006, Sheffield City Council 2010, Walton 2011). Paintings illustrating Sheffield's old water features including street flushing reflecting spring-fed water supply at Barker's Pool, and historical Crookes Valley reservoir system.
Topography	Edina Digimap / Ordnance Survey: • OS Landform PROFILE DTM (5m/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) Other: • Hydrogeology descriptions available in various studies, but most suggest no clearly defined springlines (Banks 1997, Banks et al. 1997, Ibrahim et al. 2010, Jones et al. 2000). • The Coal Authority state that pumped groundwater levels have largely recovered since historical mining activity (pers. comm. September 2011).

Table 2 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) • 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) • Clean water supply network metered areas mapped onto existing sewer flow monitoring catchments. These aligned in just one catchment, enabling an inflow/outflow water balance to be estimated.
Water chemistry methods	Water typing study (Broadhead et al. in preparation) • 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.

Table 3 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	Good	Good	Poor
Historical maps	Medium	Poor	Good
Street / place names	Good	Good	Medium
Other information	Medium	Poor	Medium
Citizen science	Medium	Poor	Medium
Topography	Good	Good	Medium
Geology and hydrogeology	Medium	Medium	Medium
Indicating stream and spring capture			
Line of evidence	**Data availability**	**Time / resource**	**Reliability**
Sewer network maps	Good	Good	Medium
Night-time minimum flow methods	Medium	Medium	Medium
Sewer water balance	Medium	Medium	Medium
Water chemistry methods	Poor	Poor	Good
Verifying stream and spring capture			
Connectivity testing	Poor	Medium	Good

Figures

Figure 1 Topographic flowpath calibration results, plotting error as average path distance (error bars show standard deviations) between known and modelled stream origins, for seven flow accumulation thresholds that set the area upstream of channel initiation.

Figure 2 Locating lost streams and springs. A – modern stream network and springs; B – historical mapped streams and springs; C – topographic flowpath modelling stream network.

Figure 3 All lines of evidence visually combined to show full stream network, including both existing and lost streams. Also shown are suspected capture sites indicated by review of sewer network maps, and capture sites confirmed by visual inspection.

Figure 4 Capture indication methodology flowchart.

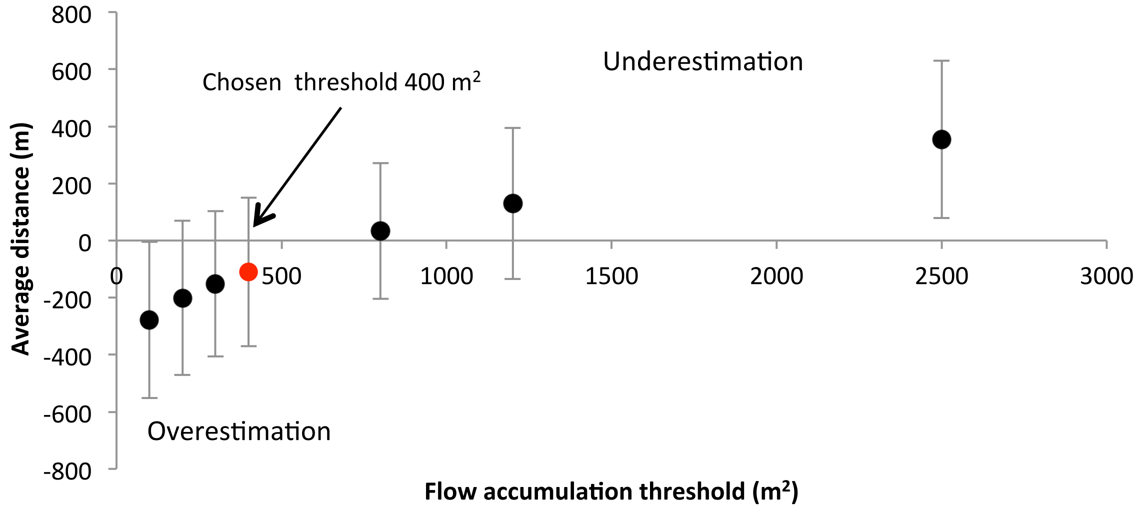

Figure 1 Topographic flowpath calibration results, plotting error as average path distance (error bars show standard deviations) between known and modelled stream origins, for seven flow accumulation thresholds that set the area upstream of channel initiation.

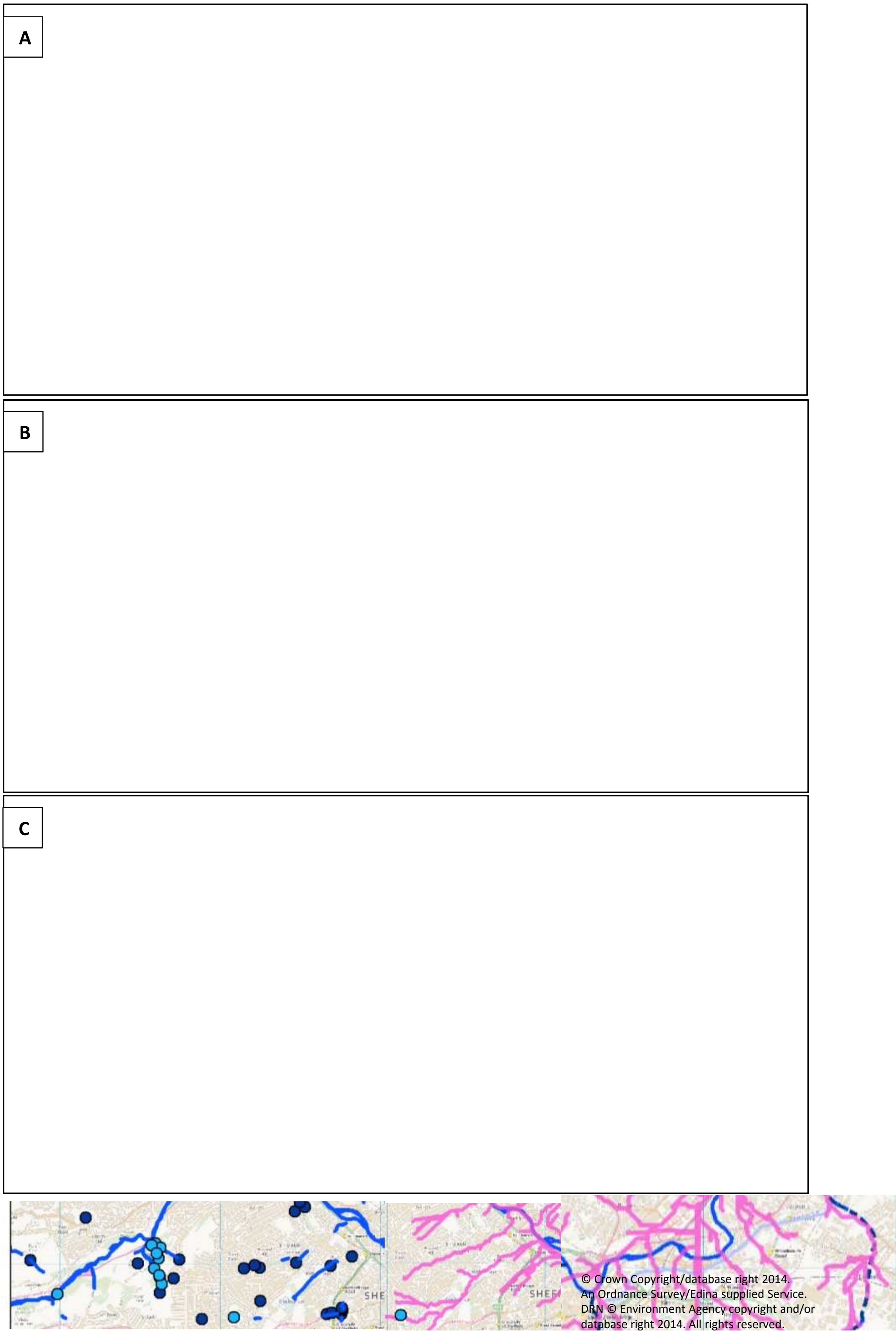

Figure 2 Locating lost streams and springs. A – modern stream network and springs; B – historical mapped streams and springs; C – topographic flowpath modelling stream network.

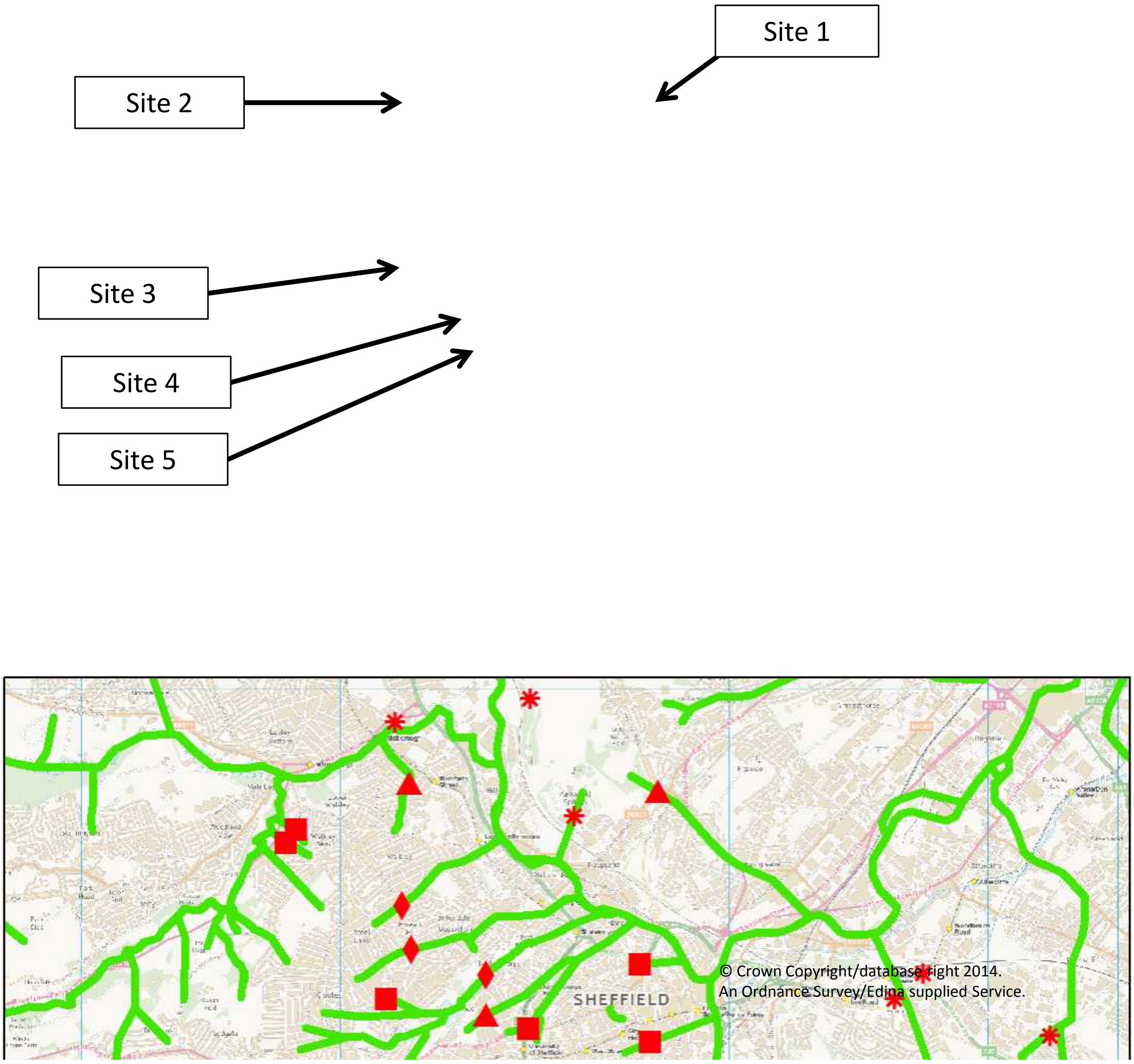

Figure 3 All lines of evidence visually combined to show full stream network, including both existing and lost streams. Also shown are suspected capture sites indicated by review of sewer network maps, and capture sites confirmed by visual inspection.

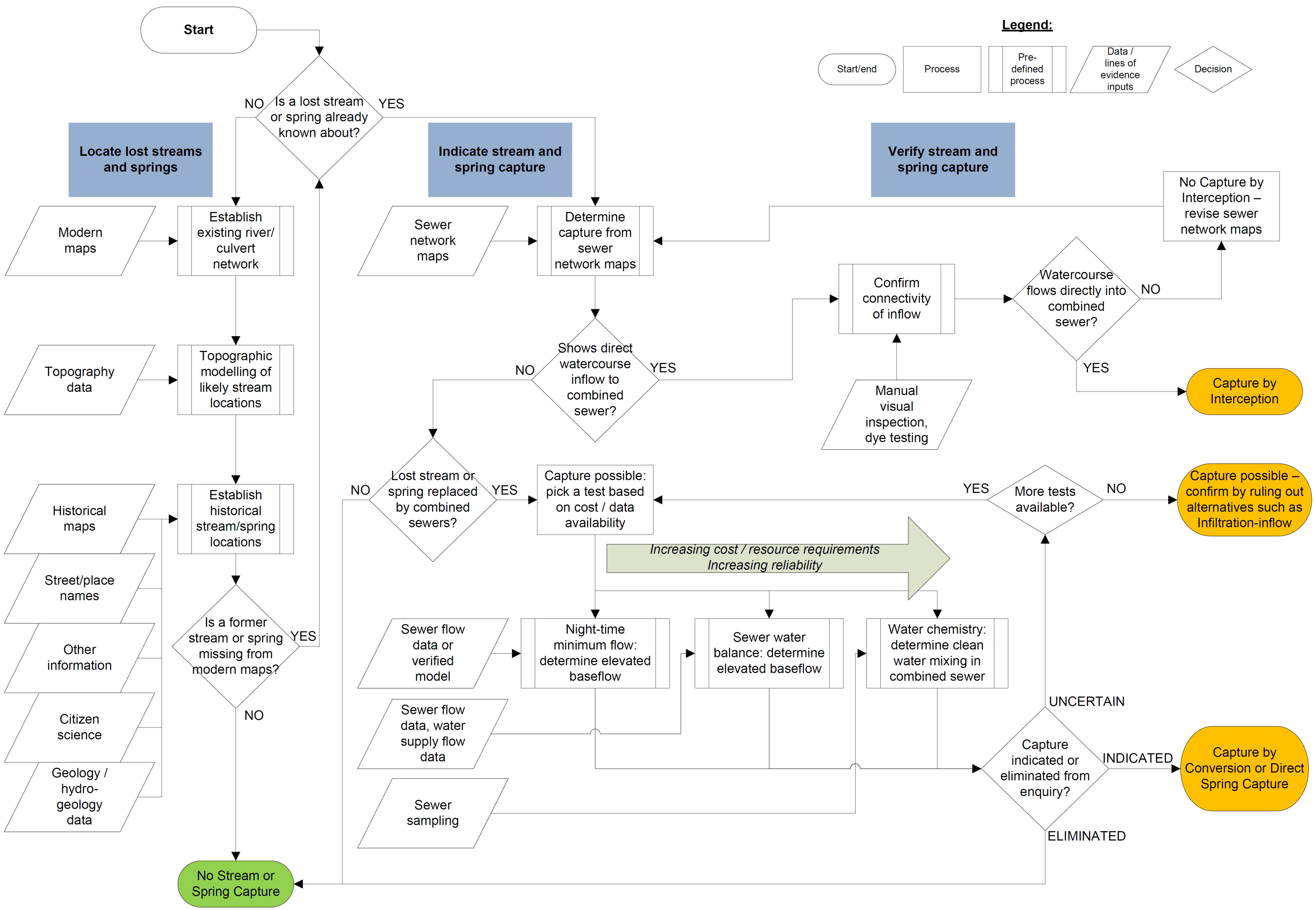

Figure 4 Capture indication methodology flowchart.