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

A. Broadhead[a,1], R. Horn[b] and D. N. Lerner[a]

[a] Catchment Science Centre, Kroto Research Institute, University of Sheffield, Broad Lane, Sheffield, S3 7HQ, UK.

[b] Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK.

Abstract

Captured streams and springs may be flowing in combined sewers, increasing clean baseflow in pipes and wastewater treatment works (WwTWs), reducing pipe capacity and increasing treatment costs. The UK water industry is aware of this in principle, but there has been no explicit discussion of this in the published literature, nor have there been any known attempts to manage it. Instead, the current focus is on the similar intrusion of groundwater infiltration through pipe cracks and joints. We have conducted a thorough review of literature and international case studies to investigate stream and spring capture, finding several examples with convincing evidence that this occurs. We identify three modes of entry: capture by conversion, capture by interception, and direct spring capture. Methods to identify and quantify capture are limited, but the experience in Zurich suggests that it contributed 7-16% of the baseflow reaching WwTWs. There are negative impacts for the water industry in capital and operational expenditure, as well as environmental and social impacts of loss of urban streams. For a typical WwTW (Esholt, Bradford) with 16% of baseflow from captured streams and springs, we conservatively estimate annual costs of £2 million to £7 million. A detailed case study from Zurich is considered that has successfully separated captured baseflow into daylighted streams through the urban area, with multiple economic, environmental and social benefits. We conclude that there is a strong case for the UK water industry to consider captured streams and springs, quantify them, and assess the merits of managing them.

Key words culvert; combined sewer; wastewater; urban streams; sewer infiltration.

[1] Corresponding author. a.broadhead@sheffield.ac.uk. (+44)114 222 5734

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 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 by increasing clean baseflow (Figure 1), 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 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).

A review for the UK water industry found many studies that have sought to map, quantify and model (physically and empirically) general groundwater infiltration 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 paper 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 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 paper. Multiple search terms were therefore used for captured streams and springs, and with so few relevant results obtained, we also reviewed the wider literature on general groundwater infiltration, identifying 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 general groundwater infiltration 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. We have found references to literature from the 1980s acknowledging the capture of streams and springs, but we have been unable 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).

3 How and why stream and spring capture occurs

From the reviewed case studies, we have identified three modes of entry of captured streams and springs to combined sewers. These are illustrated in Figure 2, and for comparison are shown with an idealised combined sewer, a CSO, and general groundwater infiltration. First we define these three types of stream and spring capture, and then we discuss the causes.

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 19^{th} 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). We must assume that, unless it is diverted elsewhere, the clean baseflow of these captured streams and springs is flowing in the combined sewers to WwTWs.

The second mode of entry (type B) is capture by interception. Following the Great Stink in London in 1853 (Inwood 1998) 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 (Barton 1992, Duncan 2011b, 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 20^{th} 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 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 general groundwater infiltration (Franz 2007, Metcalf and Eddy Inc. et al. 2004, Uibrig et al. 2002), but we reassert that 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, Mid and Low Level Interceptors 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).

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.

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, but drawing on the available information, we suggest 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 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 (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, 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 general groundwater infiltration 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 or stable isotopes.

Given the minimal published experience in identifying captured streams and springs, we can conclude that this is 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.

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 general groundwater infiltration 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 general groundwater infiltration 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), we can 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 general groundwater infiltration.

It is also important to consider the literature quantifying general groundwater infiltration 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 captured stream and spring flow, though might not be able to differentiate this from general groundwater infiltration.

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 general groundwater infiltration through pipe cracks and joints, worthy of water industry attention.

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 general groundwater infiltration, 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.

We found no case study providing 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 general groundwater infiltration and urban stream management (Ellis 2001, Franz 2007, Karpf and Krebs 2011, Schulz and Krebs 2004, Walsh et al. 2005, Wild et al. 2011), we can summarise the impact of stream and spring capture on water industry costs:

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, we have estimated the approximate effect of captured stream and spring flow on the treatment costs 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 water companies from £0.53 to £2.67 per m^3 with a weighted average of £1.05 per m^3 (Ofwat 2010b). 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. We can use stormwater prices to represent the clean captured water. These rebates average £0.32 per m^3 (range £0.18 to £0.47 per m^3) (Ofwat 2010a).

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 conservatively 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 general groundwater infiltration 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 we can reasonably assume that the charging rates must internalise the many direct and indirect consequences of increased baseflows from captured streams and springs.

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

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

We consider 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 (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 wastewater 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 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 culverted streams and springs were identified. Maps illustrate the historic burial of watercourses entering the urban area (Figure 3). While the literature does not detail the connectivity of the captured streams and springs to the combined sewer system, using the concepts in Figure 2, we hypothesise that many are interception (type B) of alpine streams flowing into the city into combined sewers. There may also be additional type A conversion to combined sewers of streams rising within the urban area. The literature explicitly acknowledges direct drainage from springs (type C) (Conradin and Buchli 2005).

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 4). 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 5). 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 our 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 daylighted 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 our estimated £33,000 annual costs of including a stream of 1 l/s from 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.

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 is 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. 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 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. We suggest that, while not a panacea, daylighting streams to separate clean flows from combined sewers could help with existing efforts 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. Protection of 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, but we suggest that the water industry considers the approach in Zurich as a means of bridging multiple goals in sustainable water management.

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 general groundwater infiltration through pipe cracks and joints. The evidence suggests that captured streams and spring have a similar impact to this: higher risks of sewer flooding and CSO spills and increased treatment costs.

We suggest 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 conclude 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.

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9 References

ALCOSAN (2012) *Draft Wet Weather Plan* (WWW), ALCOSAN (Allegheny County Sanitary Authority): Pittsburgh. (http://www.alcosan.org/WetWeatherIssues/ALCOSANDraftWetWeatherPlan/DraftWWPFullDocument/tabid/176/Default.aspx; 08/01/2013).

Antener, M. (2012) 'Rehabilitation of small urban rivers and flooding risk management in Zurich (ERZ: Stadt Zürich Entsorgung + Recycling)'. *Urban Flooding: Planning for a*

Blue and Green City, Malmö, Sweden, 14 March 2012. (http://s1011389.crystone.net/uploads/M%20Antener.pdf; 08/01/2013).

Bareš, V., Stránský, D. and Sýkora, P. (2012) 'Evaluation of sewer infiltration/inflow using COD mass flux method: Case study in Prague'. *Water Science And Technology* 66(3), 673-680.

Barton, N.J. (1992) *The Lost Rivers of London: A Study of Their Effects Upon London and Londoners, and the Effects of London and Londoners on Them*, Historical Publications: London.

Bernet, J.F. (2010) *Ecological impacts of culverts on benthic invertebrates: Habitat fragmentation and barriers to dispersal*. PhD Thesis, University of Sheffield, Sheffield.

Bienkowski, B. (2011) *Uncovering buried creek could spur Detroit development, ease sewer woes* (WWW), Michigan River News: Detroit. (http://greatlakesecho.org/2011/08/18/detroit%E2%80%99s-long-buried-bloody-run-would-flow-again-through-planned-development/; 08/01/2013).

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.

Bolton, T. (2011) *London's Lost Rivers: A Walker's Guide*, Strange Attractor Press: London.

Brooks, R.T. and Colburn, E.A. (2011) 'Extent and Channel Morphology of Unmapped Headwater Stream Segments of the Quabbin Watershed, Massachusetts'. *Journal of the American Water Resources Association* 47(1), 158-168.

Burian, S., Nix, S., Durrans, S., Pitt, R., Chi-Yuan, F. and Field, R. (1999) 'The historical development of wet-weather flow management'. *Journal of Water Resources Planning and Management* 125(1), 3-13.

Butler, D. and Davies, J.W. (2011) *Urban Drainage*, Spon Press: London.

City and County of San Francisco (2010) *2030 Sewer System Master Plan: Task 800, Technical Memorandum No. 808: Low Impact Design Implementation (Final Draft)* (WWW), San Francisco Public Utilities Commission: San Francisco. (http://www.sfwater.org/modules/showdocument.aspx?documentid=562; 08/01/2013).

Conradin, F. and Buchli, R. (2005) 'The Zurich Stream Day-Lighting Program'. *NATO Science Series: IV: Earth and Environmental Sciences: Enhancing Urban Environments by Environmental Upgrading and Restoration* 43(4), 277-288.

Cook, M. (2011) *Exploring Toronto's Sewers and Drains* (WWW), Vanishing Point: Toronto. (http://www.vanishingpoint.ca/about; 08/01/2013).

Duncan, S. (2011a) *Looking for the lost streams, kills, rivers, brooks, ponds, lakes, burns, brakes, and springs of New York City* (WWW), Psy-Geo-Conflux: New York City. (http://watercourses.typepad.com/watercourses/-about-this-project.html; 08/01/2013).

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

Duncan, S. (2012) *The Forgotten Streams of New York* (WWW), Narratively Online Magazine: New York. (http://narrative.ly/2012/10/forgotten-streams/; 08/01/2013).

Duncan, S. and Barry, L. (2010) *Unpublished paper: Modelling the Minetta Brook* (WWW), Department of History University of California: Los Angeles. (http://www.scribd.com/doc/57187219/Modeling-the-Minetta-Brook; 08/01/2013).

Duncan, S. and Head, R. (2010) *Unpublished paper: The Historiography of Urban Sewerage in the Transition from Early Modern to Modern Cities* (WWW), Department of History University of California: Los Angeles. (http://www.scribd.com/doc/57228607/Urban-Sewerage-in-the-Transition-from-Early-Modern-to-Modern-Cities; 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.

ERZ (2000) *Bäche in der Stadt Zürich (Streams in the City of Zurich)* (WWW), ERZ: Stadt Zürich Entsorgung + Recycling: Zurich. (http://www.thomas-goettin.ch/fileadmin/goettin/pdf/Fliessgewaesser_Zuerich.pdf; 08/01/2013).

ERZ (2007) *Bäche (Streams)* (WWW), ERZ: Stadt Zürich Entsorgung + Recycling: Zurich. (http://www.stadt-zuerich.ch/content/dam/stzh/ted/Deutsch/taz/Hochwasserschutz/Publikationen_und_Broschueren/ABW_Broschuere_Baeche_0709.pdf; 08/01/2013).

Ewen, M. (2012) 'Pasture Terrace: a dual solution'. *WaPUG Spring Conference*, Birmingham, 23 May 2012. (http://www.ciwem.org/media/535494/WaPUG_Paper%204-Pasture%20Terrace_Presentation%20by%20M%20Ewen_23052012.pdf; 08/01/2013).

Franz, T. (2007) *Spatial classification methods for efficient infiltration measurements and transfer of measuring results*. PhD Thesis, Technische Universität Dresden, Dresden.

Griffith, L.A. (2006) *Islais Creek reinterpreted: An exploration of restoration designs in the urbanized context of San Francisco* (WWW), University of California: Berkeley. (http://www.escholarship.org/uc/item/679901bn; 08/01/2013).

Herrmann, T. (1990) 'Brooks inside the city: example of Zurich'. *Proceedings of the Duisburg Symposium* 198(1), 287-294.

HM Treasury (2011) *The Green Book: Appraisal and Evaluation in Central Government*, The Stationary Office: London.

Hooimeijer, F. and Vrijthoff, W.v.d.T. (2008) 'International comparison'. In Hooimeijer, F. and Vrijthoff, W.v.d.T. (eds), *More urban water: design and management of Dutch water cities*, pp. 177-194, Taylor and Francis: London.

Inwood, S. (1998) *A History of London*, Macmillan Publishers: London.

Jencks, R. and Leonardson, R. (2004) *Daylighting Islais Creek: a feasibility study* (WWW), University of California: Berkeley. (http://escholarship.org/uc/item/8t5919qf; 08/01/2013).

Karpf, C. and Krebs, P. (2011) 'Quantification of groundwater infiltration and surface water inflows in urban sewer networks based on a multiple model approach'. *Water Research* 45(10), 3129-3136.

Kaushal, S.S. and Belt, K.T. (2012) 'The urban watershed continuum: Evolving spatial and temporal dimensions'. *Urban Ecosystems* 15(2), 409-435.

Kelda Group (2011) *Taking reposibility for the water environment for good: A contribution to the debate on the future of the water industry from Kelda, parent company of Yorkshire Water* (WWW), Kelda Group Ltd: Bradford. (www.yorkshirewater.com/medialibrary/PDF files/Public Affairs/Taking responsibility for the water environment for good - final.pdf; 08/01/2013).

Klass, M. (1985) 'Fremdwasser auf Klaranlagen Abwasser im Undergrund (Extraneous water in sewage works, sewage in the subsoil)'. *Korrespondenz Abwasser (Wastewater Correspondance)* 32(10), 840-843.

Lassaletta, L., García-Gómez, H., Gimeno, B.S. and Rovira, J.V. (2010) 'Headwater streams: neglected ecosystems in the EU Water Framework Directive. Implications for nitrogen pollution control'. *Environmental Science & Policy* 13(5), 423-433.

Lerner, D.N. (1990) 'Groundwater recharge in urban areas'. *Atmospheric Environment - Part B Urban Atmosphere* 24(1), 29-33.

Levine, A. (2008) *The History of Philadelphia's Watersheds and Sewers* (WWW), Philly H2O: Philadelphia. (http://www.phillyh2o.org/index.htm; 08/01/2013).

Mayor of London (2009) *The London Rivers Action Plan* (WWW), The River Restoration Centre: London. (http://www.therrc.co.uk/lrap/lplan.pdf; 08/01/2013).

Meneaud, M. (2009) *£259 million ploughed into Yorkshire Water (Wednesday 14 January)* (WWW), Telegraph and Argus: Bradford. (http://www.thetelegraphandargus.co.uk/news/4047635.__259_million_ploughed_into_Yorkshire_water/; 08/01/2013).

Metcalf and Eddy Inc., Tchobanoglous, G., Burton, F. and Stensel, H.D. (2004) *Wastewater Engineering: Treatment and Reuse*, McGraw Hill: London.

Metcalf, L. and Eddy, H.P. (1914) 'Introduction: The Lessons Taught by Early Sewerage Works'. In Metcalf, L. and Eddy, H.P. (eds), *American Sewerage Practice: First Edition*, pp. 1-31, McGraw-Hill: New York.

Metropolitan Sewer District of Greater Cincinnati (2012) *Lick Run Masterplan* (WWW), Project Groundwork: Cincinnati.

(http://www.projectgroundwork.org/downloads/lickrun/lick_run_master_plan.pdf; 08/01/2013).

Meyer, J.L. and Wallace, J.B. (2000) 'Lost linkages and lotic ecology: rediscovering small streams'. In Press, M.C., Huntly, N.J. and Levin, S. (eds), *Ecology: Achievement and Challenge*, pp. 295-318, Cambridge University Press: Cambridge.

Mühlethaler, B. (2011) 'Renaissance der kleinen Bäche (Renaissance of Small Streams)'. *Umwelt Magazine* 3(1), 32-35.

Myers, S. (2012) *Walking on Water: London's Hidden Rivers Revealed*, Amberley Publishing: Stroud.

Novotny, V., Ahearn, J., Brown, P. and Ahern, J. (2010) *Water Centric Sustainable Communities: Planning, retrofitting and building the next urban environment*, Wiley: London.

Ofwat (2010a) *Surface water drainage rebates for metered households 2009-10: Spreadsheet dated 16th June 2009* (WWW), Water Services Regulation Authority (Ofwat): Birmingham. (http://www.ofwat.gov.uk/content?id=625f3268-5a90-11de-9c48-61095c6650c6; 08/01/2013).

Ofwat (2010b) *Volumetric sewerage charges for metered households 2001-02 to 2010-11: Spreadsheet dated 5th May 2010* (WWW), Water Services Regulation Authority (Ofwat): Birmingham. (http://www.ofwat.gov.uk/content?id=8714d8f5-585c-11df-8460-ef021dc9a7ef; 08/01/2013).

Olson, J.R. and Hawkins, C.P. (2012) 'Predicting natural base-flow stream water chemistry in the western United States'. *Water Resources Research* 48(2), 1-19.

Pattacini, L., Moore, S., Burton, M., Davison, B., Gill, L., Hathaway, A., Henneberry, J., Hornby, S., Kumar, V., Morgan, E., Nunns, P., Roquette, J., Shaw, E., Stovin, V., Warren, P., Wu, L. and Lerner, D.N. (2011) *URSULA Report 9: Wicker Riverside: Sustainable development options considered by URSULA* (WWW), University of Sheffield: Sheffield. (http://www.ursula.ac.uk/upload/Inner/Outputs/Info_pack.pdf; 08/01/2013).

Paul, M.J. and Meyer, J.L. (2001) 'Streams in the urban landscape'. *Annual Review Of Ecology And Systematics* 32(1), 333-365.

Pfeiff, S.H. (1989) 'Das Problem Fremdwasser (The problem of extraneous water)'. *Korrespondenz Abwasser (Wastewater Correspondance)* 36(4), 471-481.

Pinkham, R. (2000) *Daylighting: New Life for Buried Streams*, Rocky Mountain Institute: Colorado.

Pinkham, R. (2001) *Stream Restoration and Daylighting Opportunities in the Pittsburgh Region (3 Rivers - 2nd Nature Project)* (WWW), Studio for Creative Inquiry (Carnegie Mellon University): Pittsburgh. (http://3r2n.collinsandgoto.com/revalued/stream-restoration-daylighting/stream-restoration-and-daylighting.pdf; 08/01/2013).

Platform (2012) *Twenty years ago today: 'Still Waters', Day 1* (WWW), Platform (Arts Activism Education Research): London.

(http://platformlondon.org/2012/05/01/twenty-years-ago-today-still-waters-day-1/; 08/01/2013).

Read, G. (2004) 'Development of Sewerage Rehabilitation'. In Read, G. (ed), *Sewers: Replacement and New Construction*, pp. 1-19, Elsevier: Oxford.

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.

S & P Consult GmbH (2008) *Sanierung von Abwasserleitungen und -kanälen unter besonderer Berücksichtigung der Vermeidung von Vernässung der angeschlossenen Liegenschaften (Rehabilitation of sewer pipes and ducts with reference to prevention of waterlogging of the connected property)* (WWW), Abwasserwerk der Stadt Altena: Bochum. (http://www.lanuv.nrw.de/wasser/abwasser/forschung/pdf/Abschlussbericht_Sanierung_von_AbwasserleitungenuKanaelen.pdf; 08/05/2013).

Schombert, J. (2006) *Southwestern PA Regional Wet Weather Issue: presented by John Schombert, Executive Director of 3 Rivers Wet Weather Inc.* (WWW), 3 Rivers Wet Weather: Pittsburgh. (https://courses.worldcampus.psu.edu/public/buried_assets/bios/schombertj.pdf; 08/01/2013).

Schulz, N. and Krebs, P. (2004) *WP 3 Deliverable 9: Environmental impacts of rehabilitation, Computer Aided Rehabilitation of Sewer Networks: Research and Technological Development Project of European Community* (WWW), Institute for Urban Water Management Technische Universität Dresden: Dresden. (http://www.sintef.no/uploadpages/24407/D9_Environmental_impacts_of_rehabilitation.pdf; 08/01/2013).

Smith, B.R. (2007a) *Assessing the Feasibility of Creek Daylighting in San Francisco, Part I: A Synthesis of Lessons Learned from Existing Urban Daylighting Projects* (WWW), University of California: Berkeley. (http://www.escholarship.org/uc/item/4m48c7x7; 08/01/2013).

Smith, B.R. (2007b) *Assessing the Feasibility of Creek Daylighting in San Francisco, Part II: A Preliminary Analysis of Yosemite Creek* (WWW), University of California: Berkeley. (http://www.escholarship.org/uc/item/7rm646zk; 08/01/2013).

Swiss Confederation (1991) *SR 814.20 Federal Act on the Protection of Waters (Water Protection Act, WPA)* (WWW), Federal Assembly of the Swiss Confederation: Berne. (http://www.admin.ch/ch/e/rs/814_20/index.html; 08/01/2013).

Talling, P. (2011) *London's Lost Rivers*, Random House Books: London.

The Manufacturer and Builder (1880) 'Impervious Sewer Pipes'. *The Manufacturer and Builder* 12(3), 54-55.

Troianos, D.W., Duda, B.G. and Oliver, J. (2008) 'ALCOSAN Ravine Street Stream Removal Program'. *Proceedings of the Water Environment Federation* 5(1), 752-765.

Uibrig, H., Karpf, C., Slip, M. and Krebs, P. (2002) 'Möglichkeiten der Fremdwasserbestimmung (Possibilities determining extraneous clean water in sewers)'. *Sanierung und Betrieb von Abwassernetzen (Rehabilitation and operation of sewer networks)* 1(1), 1-22.

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

United States Environmental Protection Agency (1999) *Combined sewer overflow management fact sheet: sewer separation* (WWW), Office of Water: Washington, D.C. (http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_sepa.pdf; 08/01/2013).

Unknown (2009) 'Bamberg sperrt die Bäche aus (Bamberg dams out the streams: Campaign against extraneous waters in the sewage network)'. *Umwelt Magazine* 6(1), 58-59.

US Army Corps of Engineers (2009) *Appendix A: Hydrology and Hydraulics for Sheraden Park Ecosystem Restoration* (WWW), ALCOSAN (Allegheny County Sanitary Authority): Pittsburgh. (http://www.lrp.usace.army.mil/App_A_HH.pdf; 08/01/2013).

Viele, E.L. (1865) *Sanitary and Topographical Map of the City and Island of New York* (WWW), David Rumsey Historical Map Collection: New York. (http://kottke.org/plus/misc/images-big/viele-map.jpg; 08/01/2013).

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.

Wenger, S.J., Roy, A.H., Jackson, C.R., Bernhardt, E.S., Carter, T.L., Filoso, S., Gibson, C.A., Hession, W.C., Kaushal, S.S., Martí, E., Meyer, J.L., Palmer, M.A., Paul, M.J., Purcell, A.H., Ramírez, A., Rosemond, A.D., Schofield, K.A., Sudduth, E.B. and Walsh, C.J. (2009) 'Twenty-six key research questions in urban stream ecology: an assessment of the state of the science'. *Journal Of The North American Benthological Society* 28(4), 1080-1098.

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.

Tables

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 and stream and spring capture, but not surface runoff) into combined sewers.	Extraneous clean water; infiltration-inflow; parasite flow; unaccounted for flow.
Groundwater infiltration through pipe cracks and joints	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	**Was stream/spring capture evaluated? 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 using it to divert storm runoff. 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).
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).

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
General groundwater infiltration	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

Figures

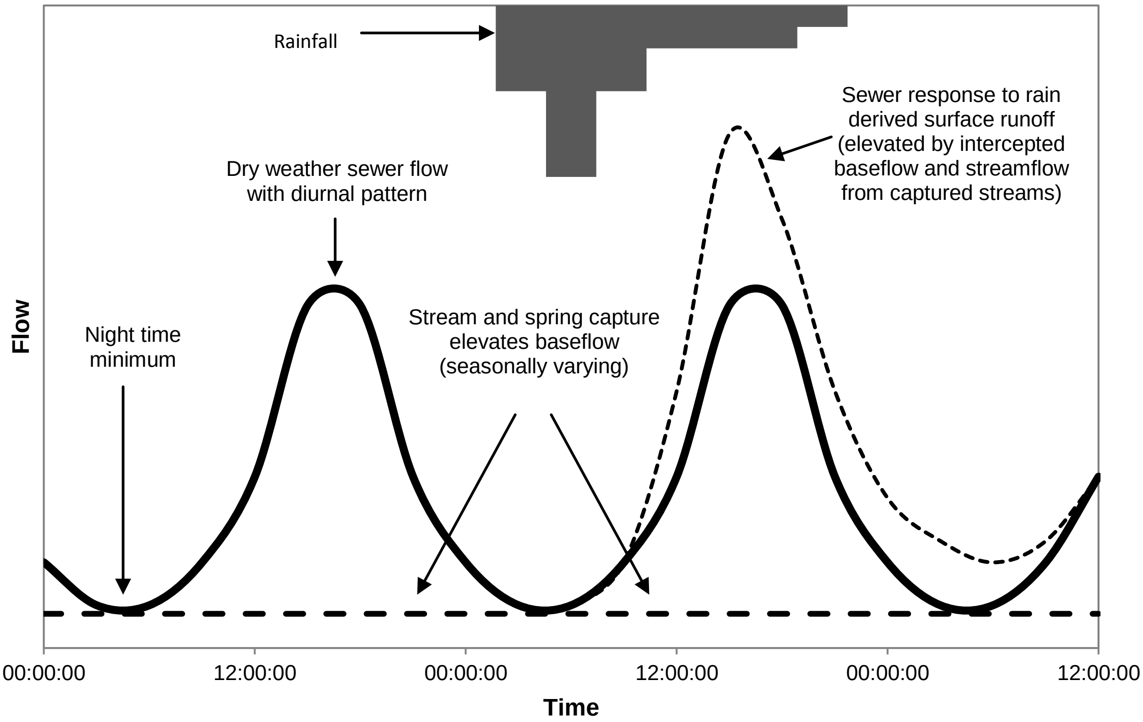
Figure 1 Idealised unit hydrograph of combined sewer flow and the effects of captured streams and springs on baseflow and surface runoff response.

Figure 2 Schematic of typical combined sewer scenarios (1, 2, 3) and the different modes of entry of captured streams and springs to combined sewers (A, B, C).

Figure 3 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).

Figure 4 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).

Figure 5 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) **Right:** daylighted Nebelbach in dense Zurich centre, illustrating innovative methods of creating engineered street streams with urban regeneration benefits (author’s own photograph).



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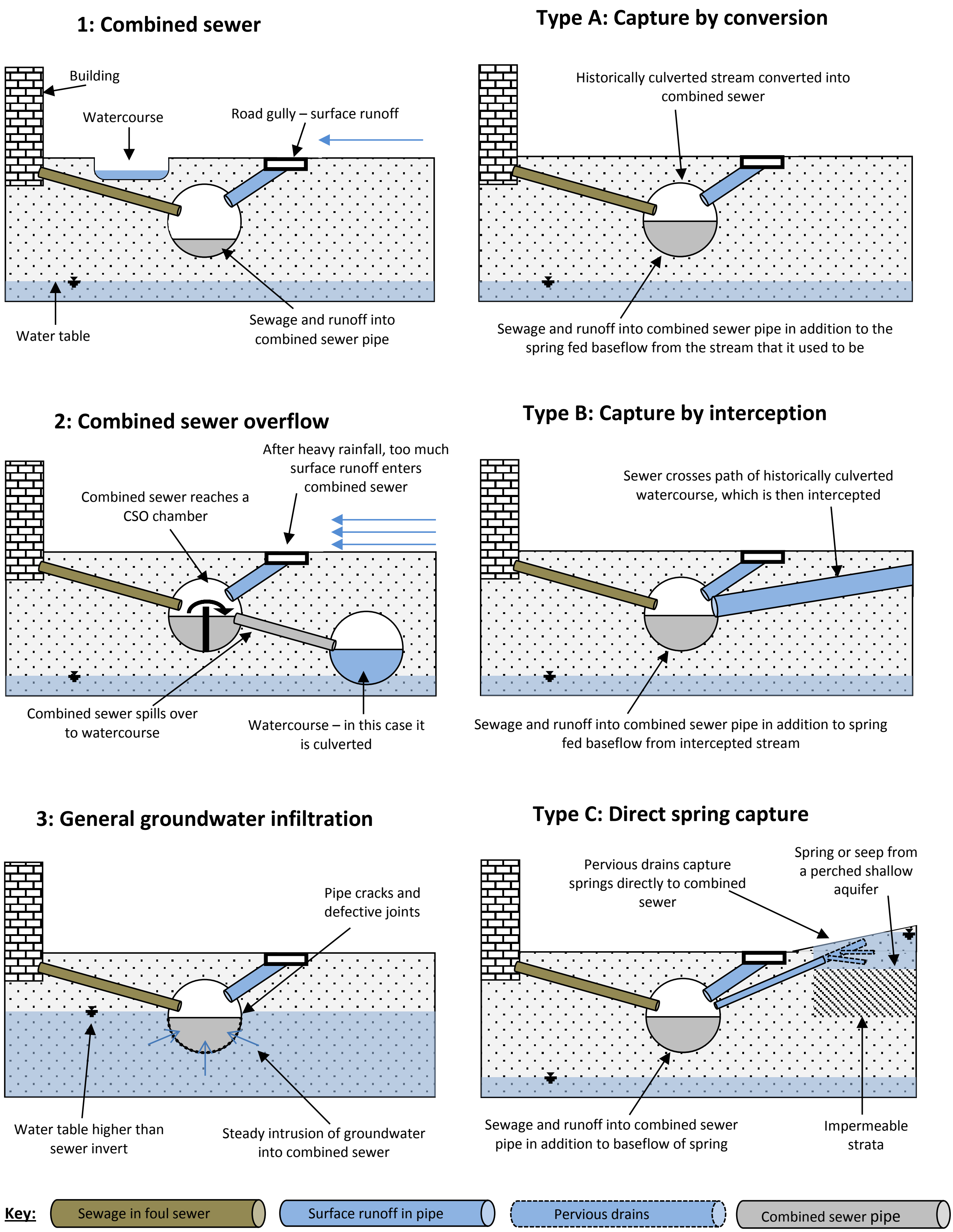

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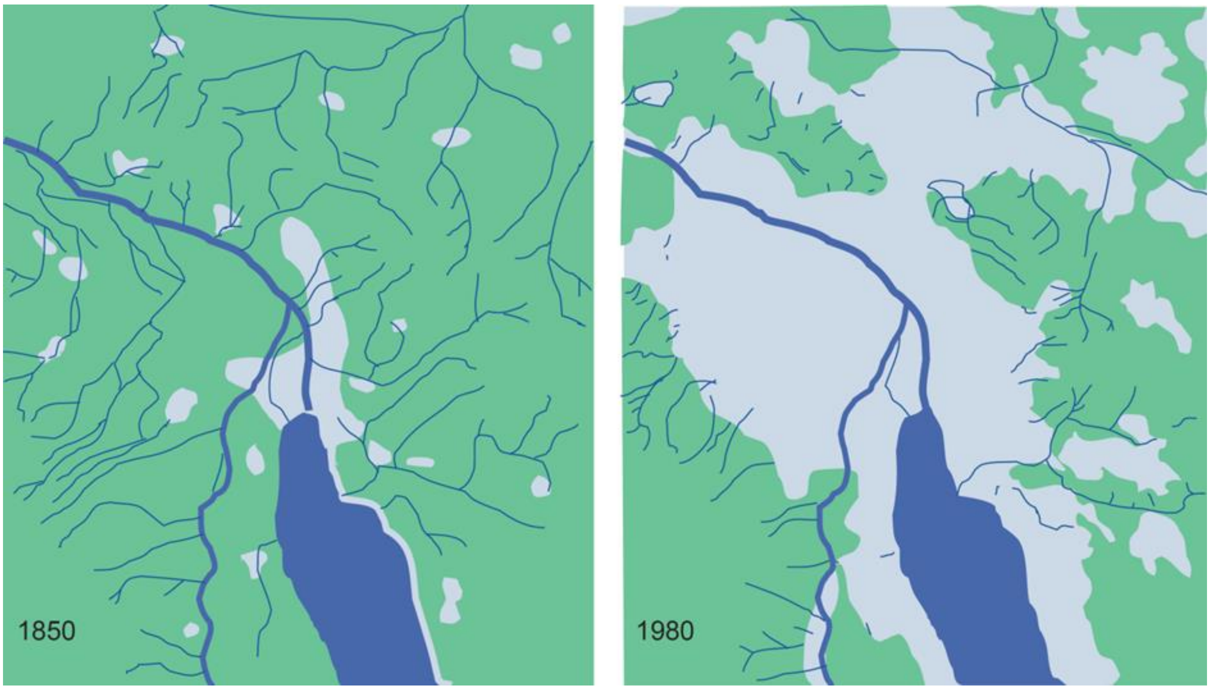

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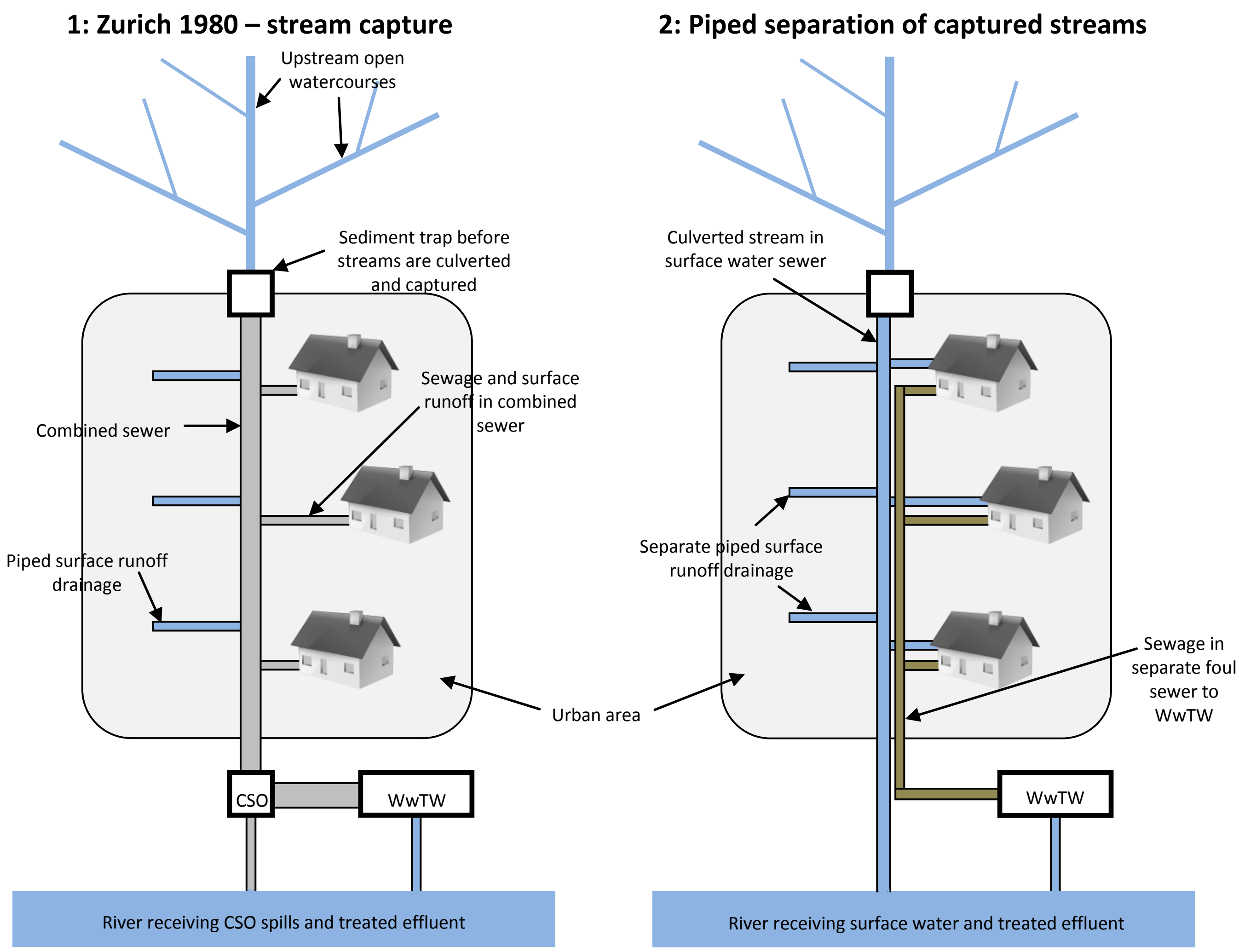

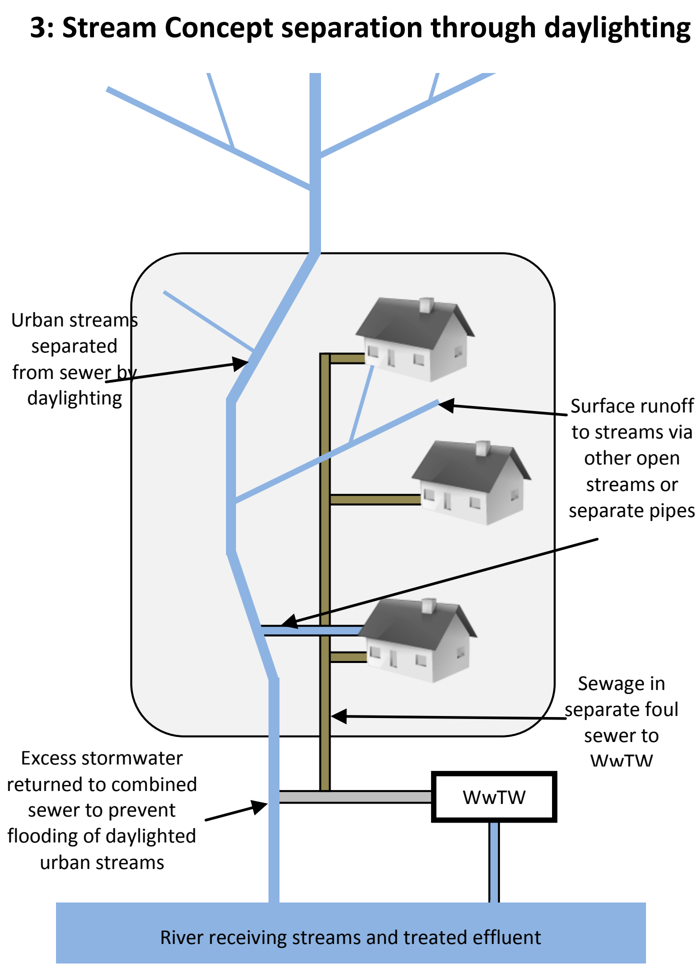

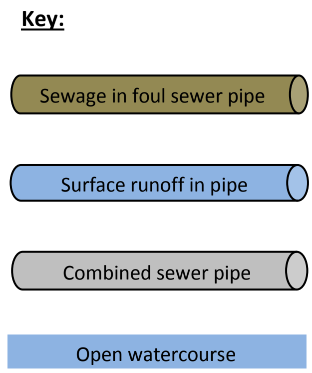

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