The Transfer and Utilisation of Low Impact Development Techniques in the US and UK

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Introduction

Combined Sewer Overflows (CSOs) are a significant environmental problem for many cities in part due to the nature of the combined sewerage infrastructure constructed in the nineteenth and early twentieth centuries in most major cities in Europe and the United States. In normal circumstances combined sewers are structured to drain both wastewater and surface water into water-based sanitation systems for decontamination before being released into the environment (Bazalgette, 1865; Beder, 1989; Halliday, 2001; Melosi, 2000). However, in order to prevent sewer flooding during high rainfall events these sewers automatically discharge untreated sewage into local rivers and other receiving bodies, including inhabited dwellings and their surrounding areas. The problem is not only the health risks that these polluted discharges present but also that they have increased in frequency as urban surfaces have expanded and become more impermeable due to paving and development. This is itself compounded by the fact that as Urban catchments increase in size base-flows of wastewater increase as a result of higher water consumption. All told this has led to a situation where the frequency of CSOs has become a significant barrier to improving water quality in many rivers and receiving bodies around the world.

While the fundamental cause of CSOs may be similar, responses to the problem vary greatly. 'Green' infrastructure solutions and technologies focus on source control of surface water in order to prevent or delay runoff into the sewers. They do this by using techniques such as green roofs, rain gardens, detention basins and infiltration systems. On the other hand, 'grey' infrastructure solutions adapt or expand conventional sewerage networks, including the building of interceptor tunnels, which are designed to collect CSO discharges before the contaminated water enters the surrounding environment. The choice between 'green' or ‘grey’ infrastructure strategies to prevent CSOs is the outcome of complex political, environmental, technical, economic and social factors. ‘Green’ infrastructure is often presented as the progressive, sustainable option, while ‘grey’ infrastructure represents a secure continuation of conventional sewerage design and management.

Interest and adoption of “green” stormwater management approaches is a relatively recent phenomenon. During the 1970s the negative impact of CSOs became the focus of environmental campaigning and government regulation in the US and UK (Karvonen, 2011; Novotny et al., 2010). Since then, engineers and urban designers have been developing a range of techniques for managing stormwater at its source in order to reduce the level of urban runoff entering the sewer system. These policies and techniques are variously known as Best Management Practices (BMPs), Low Impact Development (LID) practices, Water Sensitive Urban Design (WSUD), Sustainable (Urban) Drainage Systems (SuDS or SUDS), and Green Infrastructure.

The trend towards more localised management of stormwater are seen by some as part of a long-term trend towards more sustainable cities. Novotny et al. (2010) identify 5 paradigms of urban water management starting with the construction of sewers and moving to the focus on sustainable cities. Brown et al. (2009) trace the movement from a drained city towards the future ‘water sensitive city’ in Australia. Despite the evidence of increasing application of green infrastructure, as we will see, this is not a universal phenomenon. Rather, local conditions shape apparently technical decisions about urban water infrastructure, often negating the ability of those interested in the application of green infrastructure to fully utilise their knowledge or to transferring models from jurisdictions that have shown promising policies and techniques.

The paper begins with a summary of key legislation driving environmental actions in the US, England and Scotland. From here, we analyse some of the problems and solution to CSOs enacted in Glasgow, London, Washington DC, and Philadelphia over the past decade. This will be followed by a section comparing the key factors that shaped particular local response in London, Glasgow, Washington DC and Philadelphia. The paper will conclude with a discussion of the lessons this has to tell us about the possibilities of implementing and transferring green infrastructure solutions to stormwater management in major metropolitan areas.

Legal frameworks

The recognition of CSOs as a problem requiring governmental attention is in part a result of environmental legislation. In England and Scotland the EU Urban Waste Water Treatment (UWWT) Directive of 1991 required EU member states to institute secondary treatment of domestic and mixed wastewater discharges in settlements of more than 2,000 people and tertiary treatment of wastewater from larger towns and cities in designated sensitive areas.[1] The EU Water Framework Directive followed the UWWT in 2000. Amongst other things, this Directive expanded wastewater management to include river basin management. The goal being to achieve 'good status' for all freshwater ecosystems and water bodies across the EU by 2015.e This was itself to b followed by a second round of plans for 2015 – 2021. The

[1] Council Directive 91/271/EEC of 21 May 1991 concerning urban wastewater treatment, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:31991L0271, accessed 7 February 2016.

Environmental Agency (EA) and the Scottish Environment Protection Agency (SEPA) are responsible for river basin management planning and the enforcement of water quality standards in England and Scotland respectively. It is worth stressing that while all regions of the UK have enacted legislation designed to promote the use of SuDS in new developments; guidance through the planning process has been considerably stronger and more extensive in Scotland than England and has involved a considerably more integrated practice of SuDS use in Scotland than England (MWH, 2011; ENW, 2013).

In the United States, the core piece of legislation is the 1972 Clean Water Act (CWA) which set a goal that all public waterways should be fishable and swimmable by 1985 (US EPA, 2013; US EPA, 2014a). Despite considerable progress, by the early 1990s over one-third of America's assessed waterways were still judged as failing to meet federal water quality standards. In response, the Environmental Protection Agency (EPA) established a more stringent regime in the 1994 National Pollutant Discharge Elimination System (NPDES) permit programme. Among other steps, the NPDES mandated that regulated municipalities had to create and implement 'Long Term Control Plans' (LTCPs), in which a schedule of selected CSO controls had to be set. Municipalities that fail to adequately control CSOs face the potential of seeing considerable financial and legal consequences and can ultimately be forced to comply with a consent decree — a legally binding agreement for the control of discharge waters. Since the introduction of the NPDES, the EPA has increasingly clarified, publicised and supported the use of Low Impact Development techniques for states and localities as a way they can meet their LTCP requirements. This has led to a small but growing trend amongst cities to begin writing or reopening consent decrees to include (in some instances) significant green infrastructure components (Stoner, 2011; EPA, 2014c).

London

Greater London is a city of over 8.6 million people, covering 1,572 square kilometres. It is situated on the tidal reach of the River Thames and has an annual average rainfall of 640mm. London's combined sewerage system (built in the 19th Century) was originally designed with the belief that it would lead to overflows into the Thames no more than four times per year (on average). Over time this has increased so that it currently stands at more than 50 overflows per year on average (Bazalgette, 1865; Thames Water, 2012). In 2012 and then again in 2015 this situation led the European Court of Justice to rule that the UK was in breach of the UWWT Directive in relation to CSOs in London (http://europa.eu/rapid/press-release_IP-15-4672_en.htm).

London's existing sewerage infrastructure is owned and operated by a private company, Thames Water Utilities Ltd (Thames Water). The Office of Water Services (Ofwat) regulates investment, pricing, and other business operations, while the Environment Agency (EA) regulates abstraction licencing, discharge permits, flood protection and other environmental activities. In 2000 Thames Water commissioned the Thames Tideway Strategic Study (TTSS) to set objectives and evaluate options for 'protecting the Thames Tideway from the adverse effects of wastewater discharges' (TTSS, 2005, p.5). The Thames Tideway Strategic Study was overseen by a steering committee, chaired by independent engineer Chris Binnie, and included representatives of the Environmental Agency (EA), the Department of Environment, Food and Rural Affairs (Defra), the Greater London Authority and Thames Water, with the Water Services Regulation Authority (Ofwat) holding an observer role. SuDS and other source control measures were investigated and rejected by the TTTS. This decision was justified with arguments relating to the highly urbanised nature of the catchment area, the potential excessive costs associated with localised water catchment, the impermeability of London's clay soils, and the absence of natural receiving waters (due to the incorporation of most of London's original system of streams and rivers into the sewerage network). Rather than the use of SuDS, the final recommendation of the TTSS was that a 35km interceptor tunnel should be built from Hammersmith in West London to the Crossness Sewerage Treatment Works in the Thames Estuary. The estimated cost of the tunnel was (initially) placed at £1.7 billion (in 2004 prices). The proposal was refined to prioritise CSOs in the River Lee by constructing a separate Lee Tunnel. This reduced the length of the Tideway Tunnel to 30km, with discharge and treatment at Beckton, the site of existing wastewater treatment works in the East of London. In 2006, Ofwat commissioned a review of the TTSS study by the consultancy firm of Jacobs Babtie. The report proposed an alternative strategy of integrated stormwater management, including SuDS, two shorter tunnels, separation and real time control of stormwater in sewers, and in-river treatment. This proposal was rejected on the basis that it would not deliver the require reductions in CSOs to meet UWWT Directive requirements.

In 2011 the Thames Tunnel Commission (TTC), funded by the five London local authorities most impacted by the tunnel construction, called for a re-evaluation of alternatives, including the more extensive use of green infrastructure options, in combination with a smaller tunnel, or no tunnel. The TTC was led by John Palmer, the Earl of Selborne, and members were Jean Venables, past-president of the Institution of Civil Engineers, Richard Ashley, Professor of Urban Water at the University of Sheffield, Henry Henderson, Director of the Chicago office of the United States Natural Resources Defense Council, and Frans

H.M. van de Ven, leader of the Urban Land and Water Management team at the Dutch independent institute for delta technology (Deltares). Submission to the TTC came from local authorities, residents and environmental groups, individual experts and citizens, Thames Water and the relevant regulators and government authorities.

One of the key issues addressed by the report of the TTC was the environmental objective set by the TTSS to address the problem of CSOs in London. In the absence of any Parliamentary established specific legally binding regulatory standards for urban water quality, the TTCC chose standards to support specific fish species, using dissolved oxygen concentration as a key indicator, as well as potential public health risks and aesthetic considerations. According to the TTC setting such high environmental standards underpinned the selection of the tunnel as the only viable solution, despite its high (and increasing) cost. Alternative strategies, including green infrastructure or a smaller tunnel, were undermined by the difficulty of achieving such 'unrealistic' water quality standards (TTC 2011, p. 11).

It is worth noting that even in light of this the TTC highlighted the multiple benefits of GI compared with the single function of the tunnel as a solution to CSOs. The TTC noted that the governance and administrative structures for managing water in London undermined efforts towards integrated urban water management:

> There is a need to address current planning and funding arrangements for water and wastewater systems, as under these it is easier to construct large, costly, inflexible and environmentally impacting infrastructure systems, like the tunnel, than it is to

provide green infrastructure alternatives that deliver many benefits to society and that are adaptable to a changing climate (TTC 2011, p. 3).

In 2013 the Environment Agency (EA) undertook a further review in order to answer the specific question: 'Do we have sufficient evidence and knowledge to be confident that Sustainable Drainage Systems (SuDS) could or could not be reasonably implemented at a scale that achieves the water quality standards for the tidal Thames?' (EA 2013, 3). The report concluded that SuDS alone could not meet UWWTD standards and that the costs, benefits and timeliness of SuDS retrofitting were highly uncertain compared with the tunnel. The EA report highlighted c*omplex institutional arrangements* as a barrier to SuDS implementation, referring to a 2011 Ofwat report which compared arrangements for surface water management in England and Wales to other countries (MWH 2011).[1]

In 2014 Chris Binnie, the original chair of the TTSS steering group, published an independent report opposing the Tideway Tunnel. Binnie claimed that many of the improvements needed to reach the original objectives of the TTSS had been achieved through the construction of the Lee Tunnel and the associated improvements at sewage treatment works, and that implementation of SuDS could significantly reduce storm flows into the sewers. His change of assessment was based on developments in design, data and modelling of SuDS that were not available at the time of the TTSS analysis, and on a reconsideration of assumption about growth in wastewater base flows. Binnie was particularly critical of the revised cost estimates for the tunnel, which by 2014 had risen to £4.1 billion, compared to the original TTSS estimate of £1.7 billion in 2004. In 2005 the estimated annual increase in Thames Water customers' bills was £40, compared a maximum increase of £80 in 2015.

Despite this report, planning permission for the Tideway Tunnel was granted in August 2014. In June 2015 a new private company, Bazalgette Tunnels (operating as 'Tideway'), was formed to construct and deliver the tunnel, with investment risks underwritten by the UK Treasury. Contracts for construction of four separate sections of the tunnel have been awarded and construction began in 2016.

Despite this large-scale commitment to grey infrastructure, SuDS have subsequently received some attention in London as a strategy for surface water management, a method to relieve pressure on sewers in catchments with limited additional capacity, and for greater flood resilience. One of the better examples of this can be seen in the London Sustainable Drainage Action Plan, produced in partnership between the Mayor of London, Thames Water, Tideway, London Councils and the EA (GLA, 2015). Thames Water has itself begun to utilise SuDS in specific catchment areas in order to address existing sewer capacity constraints and surface water flooding. Additionally, most London Local Authorities have started to recommend SuDS through the planning processes. The problem that is emerging at this point is that enforcement is constrained by the lack of a policy (in England and Wales) relating directly to SuDS and new developments and retro fitting older developments.

Glasgow

The City of Glasgow has a population of approximately 606,000 residents (as of 2017) with the wider Glasgow and Clyde Valley metropolitan region having a population of just over 1.2

million individuals. The Greater Glasgow area covers 268 square kilometres along the River Clyde, and receives an annual average rainfall of 1,120mm. Glasgow began building its underground sewer network between 1850 and 1875 (in conjunction with its underground (i.e. subway) system). Under the direction of the Glasgow Corporation at the time over 80 kilometres of pipe were laid, the goal being to help address pollution and sanitary problems that plagued the city as a result of rapid industrialisation, population growth and the cities existing system of open sewers. The system was built using a series of intercepting sewers (some based on culverting existing rivers, streams, and other watercourses) that gathered wastewater to be processed at one of three newly constructed wastewater treatment facilities (Dalmarnock, Dalmuir, and Shieldhall) and then discharged into the River Clyde. Glasgow's sewers combine surface and wastewater, and as a result of the number and pollution loads of Glasgow's CSOs the River Clyde and many of its surrounding water bodies and tributaries have been classified as having 'poor' quality waters (based on the definitions established by the EU Water Framework Directive).

While pollution and CSO's were acknowledged as a problem, and there was a realisation of the imperatives of implementing the EU Water Framework Directive, it was in response to a major flooding event in 2002, which saw raw sewage deposited in the streets and basements of the city, that inspired policymakers in Glasgow to create the 'Glasgow Strategic Drainage Plan – a comprehensive assessment of drainage needs across Glasgow and the surrounding towns' (Adshead 2002, 1). To develop this plan and address the city's legacy position of decaying sewers and lack of investment, the city commissioned Hyder Consulting to bring together 'key stakeholders' including; Scottish Water, Glasgow City Council, Scottish Environment Protection Agency (SEPA), Scottish Enterprise Glasgow, and subsequently Scottish Water Solutions (a consortium of Scottish Water, other water companies and engineering contractors). The goal of this partnership was not simply to look at gray solutions but to find and promote green possibilities to addressing (or helping to address) any future potential flooding.

The partnership approach toward the development and implementation of stormwater management was carried forward with the formation of the Glasgow Strategic Drainage Partnership, later expanded and renamed Metropolitan Glasgow Strategic Drainage Partnership (MGSDP). This partnership, led by the Glasgow City Council, brought together the relevant local authorities, SEPA, Scottish Water, Scottish Enterprise and British Waterways Scotland (responsible for managing Scottish Canals under contract from the Scottish government). The partnership was tasked with finding ways to 'upgrade and modernise Glasgow's drainage and sewerage network to reduce flooding and support urban development requirements, while improving water quality and the environment' (MGSDP 2008, 1).

The role of SuDS in managing urban surface water and *helping to improve the environment* was entrenched in this process by the Water Environment and Water Services (Scotland) Act (2003) (and its subsequent amendments). These Acts redefined the term 'sewer' to include SuDS and tasked Scottish Water with the responsibility of maintaining and replacing all shared public SuDS. In Glasgow all parties have a role to play in the development and implementation of SuDS and the Scottish Government and SEPA encourage all developers to consider the use of SuDS when retrofitting buildings and properties. Despite this, there is a range of shortfalls in the 2003 Act, not least the fact that the Act only requires Scottish

Water to adopt approved SuDS systems that have been integrated into new developments. Retrofits and 'non-approved' systems remain outside the remit of the Act.

Notwithstanding this, having a requirement for the integration of SuDS in all new developments, Glasgow has seen a considerable range of SuDS projects completed over the past few years. One of the largest of these has been designed to reduce the effects of storm flooding in South Glasgow. More specifically, the neighbourhoods of East Renfrewshire, Kirkland Bridge, Kittoch Bridge were selected for SuDS redesign integrating 'flood storage areas…(which would) enhance biodiversity through the creation of artificial wildlife habitats, the creation of woodlands, scrub (lands)… wet grasslands, shallow scrapes, and ponds' (McGowan & Douglas 2014, 2). The project attenuates the flow of the White Chart, Earn, and Kittoch rivers before their floodwaters reached Glasgow. Significantly, this project was developed under the guidance of a working group of SEPA, Scottish Natural Heritage, Scottish Water, local angling groups and fisheries, RSPB, representatives from three local authorities, and involved active public consultation.

While green infrastructure is an (growing) element of Glasgow's stormwater plan, the core of Scottish Water's CSO alleviation plan still relies on traditional gray infrastructure. This is because the plan calls for the construction of several large storage and conveyance tunnels under the city, the largest being a three-mile tunnel running from Queen's Park to Craigton industrial estate. Scottish Water describes the £100 million project as: 'The biggest investment in the network since Victorian times, the upgrade will improve river water quality and the natural environment of the River Clyde and its tributaries, enable the Greater Glasgow area to grow and develop, alleviate sewer flooding and deal with the effects of increased rainfall and climate change' (Scottish Water 2013).

Where Scottish Water is integrating green infrastructure its preference for ponds, basins and large-scale underground storage tunnels is in part due to existing urban infrastructure, soil type and variation in Glasgow's average rainfall. Glasgow is built on a complex mix of soils including: wet mud and sand, boulder clay, solid rock, shale, sandstone, and quicksand. Monthly average rainfall ranges from highs of 130-140mm in December and January to lows of 60-65mm per month between April and June. As such, while SuDS are recommended or required in many documents, the primary techniques tend not to include infiltration and site-specific practices (as commonly found in the US).

While there is widespread political and industrial support for SuDS in Scotland, a 2013 report by consulting firm Hydro, 'Engineering Nature's Way', found that of the 151 respondents working in local authorities, SEPA, consulting, homebuilding, contracting and other sectors, that responded to their questionnaire, 45% felt that SuDS had only been 'somewhat successful'. This view was explained as the result of 'the constraints put in place by Scottish Water and the Local Council as to what they are willing to adopt'. In short, Scottish Water and local councils were found to be making decisions designed to make 'it difficult to use the full range of SuDS features'. As a result slightly over 84% of respondents believed that more could be done to advance the retrofitting of SuDS in urban areas. In relation to retrofitting with SuDS, one homebuilder noted: 'Whilst there is attention being paid to flood prevention in these areas, very little is being done regarding SuDS'. The problem associated with retrofitting was a belief (held by over 75% of respondents across all sectors) that there was inadequate funding for the adoption, and critically, for the on-going the maintenance of SuDS. On a positive note, as has occurred in London, as a result of the efforts to use SuDS in the control of wastewater entering the Rive Clyde both salmon and sea trout have begun to repopulate the lower Clyde.

Washington DC

Washington DC has a population of over 600,000 residents (over 5 million in the greater DC metropolitan area) and occupies 158 square kilometres (68.3 square miles) at the confluence of the Anacostia and Potomac Rivers. DC has an average rainfall of 1,160mm and sits in the heart of the Chesapeake Bay watershed, which is currently threatened by hypoxia and eutrophication, despite significant efforts by DC and other watershed stakeholders to address the situation (Boesch et al. 2001; Chesapeake Bay Program, 1987; National Research Council 2008).

Washington DC operates under direct federal control or oversight. The federal government owns 40% of the land; including much of that immediately adjacent to the district's major water bodies (Chesapeake Bay Program 1996). The District of Columbia Water and Sewer Authority (DC Water) is responsible for managing the district's combined sewers and the Blue Plains sewage treatment plant (whose finances are not tied to DC's overall budget) (DC Water 2012b; DC Water ndd). The District of Columbia Department of the Environment (DDOE) is also integrally involved through management of separate storm sewers and the management and regulation of DC's waters.

Annually Washington DC has over 60 CSO events (triggered by rain events as minuscule as 2.5mm), which continue to be a major source of harm for receiving waters (DC Water 2002).

In response to legal suits in relation to CWA violations (and a 2005 consent decree), DC Water created the 'Clean Rivers Project,' Long Term Control Plan (LTCP) (US District Court for DC 2003). This plan has been designed to reduce CSO overflow volumes in the city by 96% to an estimated 138 mg/avg per year at an estimated cost of $2.6 Billion (in 2001 dollars) (DC Water, 2012b; DC Water, 2014b). The plan originally featured the creation of four storage and conveyance tunnels and $3 million devoted to LID retrofits, largely in the form of demonstration projects (DC Water 2012b). Reasons given for the lack of more extensive use of LID were: lack of information; the high rate of CSO reductions required; and short timetable set for improvements (Ray 2014). The last two considerations were particularly acute in DC, because of its location in Chesapeake Bay watershed.

While grey infrastructure was the primary component of DC Water's original LTCP, other city agencies have encouraged the use of green infrastructure through a variety of policy and planning instruments, designed to address broader water quality issues. For instance, DDOE's RiverSmart Homes program provides consultation and subsidies to property owners for onsite stormwater management (DDOE ndb). In 2010 DDOE and DC Water began to assess stormwater removal fees tiered to impervious area (DDOE, ndc; DC Water nde). In 2013 DDOE released guidelines requiring all new construction greater than 465 square metres to retain the first 30mm of rainfall or to combine on-site and off-site retention through their Stormwater Credit Trading programme (DDOE 2013). In 2013, the DC Department of Planning instituted the Green Area Ratio, a planning instrument that requires all new development and significant renovation projects to incorporate green landscape elements (DDOE 2014).

In 2014 DC reopened its consent decree in order to include a significant green infrastructure requirement. While a range of factors influenced this decision, the primary driver was amount of new information relating to LID's stormwater benefits and advantageous financial costs that has emerged since the first consent decree was signed. In addition, the EPA clarified and subsequently promoted the role and transfer of green infrastructure for meeting regulatory requirements. There were also changes in DC Water. Amongst these was the decision to hire George Hawkins as CEO and General Manager in 2009. Hawkins' had a background as an environmental advocate, director of the DDOE, and chair of the committee to develop DC's sustainability plan (http://www.dcwater.com/about/hawkins.cfm). Adding to all of this, the substantial financial implications of the current consent decree became increasingly clear, in particular its effects on low-income residents (DC Water 2014b; Ray 2014).

In 2016, the *Long Term Control Plan Modification for Green Infrastructure* was officially accepted. This plan fully replaces one of the planned CSO interceptor tunnels with a green infrastructure investment of $90 million, addresses overflows into the Potomac through a combination of grey-green infrastructure, and gives the city an additional five years to complete the project. DC Water justifies this change citing added social, environmental and economic benefits, reduced financial impact on ratepayers, and synergy with the Mayor's Sustainable DC Plan (DC Water 2014b; DDOE nd). While community and advocacy groups generally support the inclusion of green infrastructure, concerns about the plan have been articulated. These include:

1) The effects of delays in the timetable relative to the initial LTCP;

2) Accountability being tied to budget spent on green infrastructure rather than environmental outcomes;
3) Insufficiently articulated maintenance and repair costs and protocols;
4) The clustering of green infrastructure projects within the city—significantly *not* in some of the poorest communities neighbouring the Anacostia River (NRDC, nd; Chavez, 2014; Fellows, 2014).

Philadelphia

Philadelphia is the sixth largest US city, with a population of over 1.5 million (down from 2 million in the 1950s) occupying 347 square kilometres. Despite high levels of poverty (26%), in many ways Philadelphia has been a pioneer in water management. It was the first US city to take responsibility for the water supply in 1801 and subsequently created the 45-hectare Fairmount Park in the middle of the city to protect the city's water supply (City of Philadelphia nd). More recently the Philadelphia Water Department (PWD) was created in the 1950s as a municipally owned and financed department, to manage drinking water and wastewater services. Currently, the PWD maintains three wastewater treatment plants and nearly 4,828 km of sewers (60% of which are combined) within the city and neighbouring 596 square km of suburbs (Holst 2007). Philadelphia receives about 1,043 mm of precipitation per year and has well-drained soils, yet—due to development on historic tidal marsh—experiences flooding and subsidence in some areas (PWD 2009).

Several developments paved the way for Philadelphia's approach to stormwater management. First, the region has been influenced by planning and landscape practitioners who trained with The University of Pennsylvania's Ian McHarg (raised in Glasgow), whose 1969 book *Design with Nature* is the cornerstone text developing the concept of ecological planning. Second, de-industrialisation challenges, particularly abandoned properties and vacant lots have galvanised and unified many non-profit organisations and city agencies for over 20 years (Pennsylvania Horticultural Society 1995; City of Philadelphia nd). Third, PWD has a long history of thinking of land-water interconnections and of regional watershed management. Led by Howard Neukrug, the PWD developed the Office of Watersheds in 1999 to better address the formerly separate operations of CSO management, stormwater management and source water control watershed-wide (PWD 2009). Crucially, that Office defined its mission broadly, stating, 'government agencies (must) break out of their traditional roles of providing narrowly defined services' (City of Philadelphia 2011).

In order to comply with the Clean Water Act, PWD conducted a cost benefit analysis of a range of CSO management options utilizing a 'Triple Bottom Line' assessment methodology (Stratus Consulting 2009). This approach compared costs of potential projects that included an assessment of wider social, economic and environmental benefits of each option. In this report, green infrastructure compared favourably to grey alternatives. Of note, they found that this was primarily due to non-water-related benefits including reductions in heat-stress mortality, improved aesthetics and property value, and increased recreational opportunities (Maimone et al. 2011).

Based on these findings the PWD created the Long Term Control Plan: 'the single largest investment in the City's environment over the next 25 years…presents a unique opportunity to be much more than just a water quality improvement program.' Philadelphia's 2009 'Green City, Clean Waters' plan sets out an agenda spending $2.4 billion between 2011-2026, 67% of which will be spent on green infrastructure techniques (DeGood 2013). This is a commitment to reshape the city (US Housing and Urban Development 2013) by developing 'the most extensive urban network of green infrastructure in the United States', and using Philadelphia's vacant land as a resource (Natural Resources Defense Council nd).

This plan was formalised through a Consent Decree and Partnership Agreements with the EPA and state authorities (EPA 2015). The objective, create 9,500 'Greened Acres' over 25 years. That is, to convert nearly 40.5 km^2 of impermeable surfaces to manage 25mm of runoff onsite and reduce overflows by 85% through projects on both public and private property (Maimone et al. 2011; Water Environment Federation 2014). The city owns approximately 45% of impervious surfaces within the CSO area and will integrate green infrastructure into capital improvement projects on city-owned streets, sidewalks, and properties. Other public land projects include a large-scale street tree planting programme; preserved open space—including dedication of vacant and abandoned lands, and stream restoration (City of Philadelphia 2011; US Housing and Urban Development 2013).

The PWD has created requirements and incentives for green stormwater management on private property; including rain gardens, green roofs, street trees, porous pavers, and other green interventions. Beginning in 2010, the PWD adopted a parcel-based billing system for commercial properties. These assess fees in proportion to the amount of impervious surface. A geographical information system (GIS) supports this programme so that property owners can view information about their parcel's imperviousness online (Cunningham 2011). In addition to greater equitability, this system encourages green retrofits (Valderrama et al. 2012). Grant programmes also provide technical and financial assistance and encourage project aggregation for commercial property owners (Valderrama et al.

2013; PWD 2015). As of June 2014—five years into the 25-year planning period—the city had created 1.3 km^2 of newly pervious area (City of Philadelphia 2014).

Discussion

Table 1 summarises some of the central factors that influence urban environmental decision-making in our case study cities (that potentially impact upon the transfer and knowledge updating processes). In the first instance, it is clear that local environmental conditions such as rainfall, water quality of receiving bodies, soil types, and even climate change forecasts (and perceptions of these), influenced the technical feasibility of adopting and implementing different green and gray infrastructure options. We want to stress that feasibility not only influenced technical abilities to adopt different green techniques, but it also impacted perceptions of how useful other systems could be in solving CSO issues and in the absence of leadership often how interested policymakers were in how other systems were responding to CSOs and water quality issues.

Table 1. Comparing responses to Combined Sewer Overflows in Four Cities

	London	Glasgow	Washington DC	Philadelphia
Environment	Mostly clay soils. 640mm annual rainfall, evenly distributed. More intense storms predicted. Rivers Thames and Lee receiving CSOs, poor water quality. Dense urban form.	Mixed Soils. 1,120mm annual rainfall, unevenly distributed. More intense storms predicted, River Clyde receiving CSOs, rated poor water quality. Dense urban form.	1,160mm annual rainfall, evenly distributed. Within sensitive and degraded Chesapeake Bay watershed. Dense urban form.	Well drained soils. 1,055mm annual rainfall, evenly distributed. Development on historic tidal wetlands. Subsidence problems. Dense urban form and vacant land problem.
Regulation	EU UWWT Directive. Limited national guidance or drivers for SuDS.	EU UWWT Directive. Consistent national support for SuDS.	Clean Water Act. Additional water quality requirements given location in Chesapeake Bay watershed.	Clean Water Act.
Governance	Private ownership of infrastructure. EU Directives. Local government	Public ownership of infrastructure via Scottish Water. EU Directives.	DC water is independent authority of DC. DDOE manages MS4s	PWD is municipally owned and financed.

	jurisdiction uncertain.	Range of Scottish Acts and building regulations.	and responsible for receiving water quality. Federal ownership of 40% of land area.	
Economics	Regulated monopoly, funded through water bills. Private capital investment. High land values.	Regulated monopoly, funded through water rates. Mixed land values.	Funded through user fees, grants and bonds. DC Water's finances are not tied to DC's overall budget.	Funded through user fees, grants and bonds.
Society	Resistance to tunnel from some engineers, local authorities and environmental NGOs. Little wider engagement with CSOs and tunnel beyond communities impacted by construction. Recreational water users in favour of tunnel.	Most feel more could be done to retrofit SuDS. A majority believes more should be done in the upkeep of SuDS systems. Most believe legislation has been why Scotland is ahead of England and Wales in the implementation of SuDS.	Great income disparity (nearly 20% of DC households live in poverty). Some resistance to GI among those with a focus on environmental justice. Focus on water quality in Chesapeake Bay.	High levels of unemployment, poverty, and property vacancy. Many agencies and non-profits, which have cooperated to manage vacancy problems. Local emphasis on ecologically sensitive planning.
Leadership	Thames Water and regulators in agreement about tunnel solution.	Multi-stakeholder partnerships.	New management—George Hawkins—leads in new direction; background in environmental advocacy and sustainability.	Howard Neukrug and Water Department as regional leader.

This issue most clearly seen in London where the soil and receiving water body were seen as dictating the need for a gray-solution and the non-viability of SuDS solutions. More specifically, London's clay soils and high density urban form were a point of contention as proponents of the tunnel claimed that they constrained opportunities for infiltration and local storage of stormwater. Thus, tunnel proponents were able to use environmental conditions as a way to resist the transfer and use of more sustainable infrastructure solutions. Further complicating the development (and potential capability to learn from others) the Thames Tideway Strategic Study was accused by opponents of the Tunnel of artificially inflating the sole environmental objective of unpolluted water quality rather than taking into consideration the wider environmental benefits offered by green infrastructure. At the opposite end of the spectrum, Philadelphia's well drained soils and substantial areas of abandoned land made a perfect canvas for the use of green infrastructure solutions. In this Philadelphia not only developed indigenous solutions but also look around for BMP and EPA promoted solutions in their efforts to adopt green solutions to their CSO problems.

The governance of urban drainage infrastructure including ownership patterns and planning and regulation structures also influences the selection of stormwater management techniques (and the willingness and ability of policymakers to engage in the transfer process). London was unique of the four case study cities in that its drainage, sewerage and wastewater infrastructure are privately owned. Not only did this negate interest in and use of transferred solutions but, the separation of privately owned infrastructure and public responsibility for urban planning in London, was considerably less conducive to institutional integration and flexibility than we found in other cities, particularly Glasgow, which placed considerably greater emphasis on the use and integration of green infrastructure in combatting their CSO problems.

Another lesson we found is that where responsible agencies able to take a more holistic approach to their responses to CSOs appear more likely to examine and adopt green infrastructure solutions. This included looking to what others were doing in order to see if there were lessons they could borrow and apply though a wider range of planning and regulatory instruments. It appears that the key to this is the ability of decision makers and stakeholders (particularly those working in the relevant water department) to broadly define their service provision requirements helping them to actively alter the focus from gray to green. This is most clearly seen in the case of the Philadelphia water department, which was able to focus entirely on LID once it began to view its mission to include the non-water benefits that could be provided by LID techniques. Scottish Water (while not acting alone) was also able to view the issues surrounding CSOs in Glasgow more broadly, which allowed them to include a range of non-water benefits (including enhance biodiversity and artificial wildlife habitats) in their calculations as to the best way to deal with CSOs.

Systems, which are able to interpret their water remit broadly, are also more likely to engage in the transfer and learning processes than those who maintain a tight understanding of water resource management as simply the movement of water from point A to point B. As part of this, we expect that while transfer is occurring, many of the systems that are experimenting with green infrastructure will be producing their own solutions based on fairly diffuse knowledge related to SuDS that floats around in the ether surrounding water management.

Both economic context and ownership patterns of water related infrastructure influence the viability of different options for reducing CSOs and thus the types of transfer and degree to which those involved engage in the knowledge updating process. In the first instance private ownership, secure income (through regulated water charging), and central government underwriting appeared to encourage the development of gray infrastructure solutions. Part of this is due to the capital investment required for large scale gray infrastructure projects is more likely to emerge in these situations, thus reducing the need and desire to engage in the transfer or consideration of green infrastructure solutions. This is most clearly seen in London where the decision to pursue the interceptor tunnel (over SuDS) was in part due to the private ownership of the infrastructure and its ability to raise the considerable amount of private capital necessary for major gray infrastructure projects. By contrast, municipal governments and public sector ownership patterns in Washing DC and Philadelphia constrained the ability of water resource managers to raise similarly large amounts of capital. This situation in part led both cities to actively pursue and engage in the transfer of LID technologies and techniques. The need to find onsite solutions to the issue of CSOs was compounded in both DC and Philadelphia by the inability of the water resource managers to increase sewer charges. Combined, these two factors provided a powerful driver for less capital-intensive infrastructure solutions.

Social drivers in decision-making about drainage are also evident in the use and integration of green infrastructure, particularly as they related to urban regeneration planning in post-industrial Glasgow and Philadelphia. Part of this can be seen as falling into the environmental justice concerns of the communities relating to the unequal burden and impact CSOs have on poor neighbourhoods. Unlike the other three cities social engagement in London has mostly been limited to protests by residents and local politicians in boroughs most impacted by the construction of the tunnel, and support by recreational users of the Thames.

The social drivers surrounding the use of green infrastructure solutions was also linked to the massive decline in populations seen in both Glasgow (from a high of over 1.1 Million in the early 1940s) and Philadelphia (from a high of just under 2.1 Million in the 1950s) followed by almost a decade of growth since 2010. This decline and growth created social configurations that helped foster the acceptance of green infrastructure solutions as a way to both enhance land values and engage in neighbourhood renewal and beautification. At the same time London has seen its population continue to grow since the mid-1970s (from just over 7.5 million in 1975 to over 10.5 million in 2017). Instead of having issues of to little water in the sewer systems and vacant land London has had the opposite problem of too much growth for the existing sewer system, thus creating entirely different set of social (and infrastructure) pressures and issues. When viewed through the social, the adoption of green infrastructure illustrates the complexity of attempting to design any single SuDS policy or best practice solution that could act as a basis of transfer and knowledge updating for more than a limited number of systems. As such, it is likely future studies will find a range of policies being used and transferred across the globe. In this it is also likely that patterns of convergence might have little or nothing to do with the transfer of a given policy but are in fact the result of the legal and financial frameworks local governments find themselves operating under.

The role of strong local leaders in making the case for green infrastructure solutions was evident in Philadelphia, Washington DC, and Glasgow but notably absent in London. In London the main proponents of SuDS solutions were outside Thames Water and key regulators and decision makers, and were therefore positioned as opponents to the tunnel. In Glasgow and the US cities, strong individual leaders within the water utilities and city government were able to demonstrate not only the wider values of green infrastructure but also demonstrate what other systems were doing to achieve the active integration of green infrastructure into their water management planning. Moreover, the leaders in Glasgow, Philadelphia, and Washington DC were able to achieve change across institutions by linking to broader environmental and sustainability objectives despite some uncertainty about green infrastructure implementation at scale and related costs, including maintenance.

Conclusion

Combined sewers represented a standard engineering response to nineteenth century public health crises, but responses to the problem of CSOs these systems are designed to generate have led to a range of new problems in the twenty-first century. In the US, legal action required cities to address CSO problems through the development of long-term control plans. As a result many have experimented with some form of green infrastructure solutions. In this, while the EPA encourages the use of low impact development techniques and technologies local environmental, economic, political and social conditions are shaping technical decisions about how to solve CSOs. Comparing London, Glasgow, Washington DC and Philadelphia shows that the choice of 'green' or 'grey' is dependent on diverse range of factors including amongst others: public or private ownership and control of the core water related industries and infrastructure; the ability to raise capital for large-scale gray investment; institutional flexibility; local leadership and their views toward green infrastructure; international national, and local regulatory frameworks; urban social context; and technical constraints.

As post-industrial cities follow different economic, social and political pathways, their infrastructural choices becoming both more alike in general but divergent in specifics. This divergence will both facilitate the transfer of green infrastructure techniques and negate against it. Where the leadership exists alongside institutional flexibility it is likely that decision-makers will have the ability to learn from others. However, where the social-economic situation and ownership patterns are constrained less learning is likely to occur. For instance, in the development and use of green infrastructure solutions viable in Glasgow, Washington DC and Philadelphia a number of lessons were borrowed from others.

Helping to facilitate this was the fact that the drainage infrastructure is still publically owned and wider ranges of policy instruments are available to promote sustainable and decentralised solutions. In contrast, an interceptor tunnel was almost seen as the only viable solution to CSOs in London where the institutional, economic and regulatory structure of the water industry encouraged large-scale capital investment projects.

While proponents of green infrastructure frame these solutions within narratives of progress towards urban sustainability, the complexity of urban development and infrastructure governance means that this may not be the next paradigmatic, universal response to urban drainage challenges.

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[1] It is worth noting this finding. Most studies of transfer and knowledge updating focus o the movement of ideas and policies. In this instance policymakers looked around and used this information to prevent the development and implementation of SuDS solutions in London: the opposite of what most studies discuss when looking at the transfer process.