



**Retrofitting urban drainage infrastructure: green or grey?**

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Complete List of Authors:	Dolowitz, David; University of Liverpool, Politics Bell, Sarah; UCL, Dept of Civil, Environ & Geomatic Eng Keeley, Melissa; George Washington University, Department of Geography
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## Retrofitting urban drainage infrastructure: green or grey?

### Reviewer Comments

A somewhat generalised descriptive approach which lacks quantitative evidence/detail of costs/benefits, flow volume reductions, water quality targets and performance etc., as a basis for moving towards (or away from) a "green" solution. The Introduction is rather mundane and overlooks the interaction of combined and separate systems and the nuanced economics, legislation and administrative/political pressures and influences on existing and future drainage infrastructure implementation as well as operational management. It also overlooks the issue of whether GI is a necessary precursor framework (and if so why), for successful SUDS/BMPs. Or can stand-alone SUDS controls provide a "better" strategy to resolving surface water problems under certain conditions and circumstances?? The paper to some extent suffers from starting out with objectives of CSOs and then tracking into surface water issues. The two are obviously related but their interaction and feedback is complex but clearly leads to a need to discuss the relative merits of the differing networks and this is missing.

#### RESPONSE:

The introduction has been rewritten to clarify the purpose of the paper, and to highlight the complexities raised by the reviewer. The focus of the paper is responses to CSOs, not the barriers to implementation of SUDS/BMPs. As such the question of whether wide-scale GI projects or stand-alone SUDS strategies are more likely to support higher uptake of SUDS techniques is outside the scope of this paper. The paper does not seek to evaluate which is a 'better' strategy, but to demonstrate the complex interactions between local factors that determine responses to CSOs. The introduction and discussion throughout the paper have been revised to clarify this focus. Surface water management is a key contributor to CSOs and their prevention, but the surface water management itself is not the focus of the paper.

There are also clear differences between the "promotion" of SUDS/BMP legislation (such as in the UK) and that of mandatory statutory legislation (as in the US and Australia). The reasons for these fundamental differences in attitudes and approaches are not really developed or teased in the critique. The scale of resistance and legal challenges to even the US mandatory system is not discussed and this is disappointing.

#### RESPONSE:

In the Legal Framework subsection discussion, and conclusion we have clarified differences in the regulatory climate surrounding CSOs in the US and UK. Certainly, in the US, there is intense legal pressure to manage CSOs. Yet, while the regulatory environment in the US is increasingly open to green infrastructure, cities have flexibility in choosing CSO abatement strategies. Indeed, most US cities have implemented 'Long Term Control Plans' emphasizing "grey" infrastructure strategies, often setting aside little more than funds designed to operate LID demonstration projects. Philadelphia is the only US city we are aware of that has utilized a CSO abatement approach based primarily on green infrastructure.

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Finally, the legal situation surrounding stormwater management in the US is complex. Cities (or their water management agencies) being sued to manage CSOs is simply how environmental regulation works in the US. Otherwise, most of the legal challenges we have witnessed are around stormwater fees and billing systems, which we have deemed beyond the scope of this paper, as this is problematic regardless of the abatement strategy chosen.

The situation in London (p4/5) is also very much simplified and overlooks the role of lower tier LAs within the Greater London authority in respect of surface water drainage as well as the difficulties posed by the introduction of upper tier LLFAs. The Thames Tideway Tunnel (p5-9) disregards the very considerable opposition to the centralised super-tunnel (especially by Hammersmith/Kensington boroughs for example) and the evidence presented for an alternative decentralised approach. The political element in the debate is entirely missing--the Jacob Babbie report is mentioned but other significant studies (e.g that of Ashley) are overlooked. Particularly in respect of rebuttal to that of the EA (2013) report. It is also not true that LAs in the UK require SUDS in all development proposals; they are still only advisory in nature and cannot be mandated as such especially if they are deemed to be "economically disproportionate". The assertion that London soils are not suitable for infiltration SUDS is also based on assumptions, which have been consistently challenged. One only has to refer to the large number of soakaways for both highways and domestic roof surfaces to demonstrate that this assertion is far too sweeping.

#### RESPONSE:

The London case study has been revised to provide greater detail of the findings of the Thames Tideway Commission, which provided a focal point for objection to the tunnel for local authorities such as Hammersmith and Kensington, and included Richard Ashley as a member. This includes key objections to the tunnel based on environmental standards, sewer base flow forecasts and the multiple potential benefits of GI. Within the constraints of the paper we judge this to be the most effective way of synthesising the range of positions and publications in opposition to the tunnel and in favour of GI. The description of the current advisory nature of planning decisions regarding SUDS has been clarified, and the arguments about clay soils are presented as the view of the tunnel proponents. The main point is that clay soils were used as an argument against SUDS, despite the challenges highlighted by the reviewer.

The paper needs to adopt a much more critical and analytical appraisal of the technical, economic and political nuances, which confound the implementation of a widespread adoption of SUDS/BMP drainage infrastructure in many European countries including the UK. Would the successful elements embedded in Australian and US practice be transferable to UK conditions??

#### RESPONSE:

The introduction now clarifies –

The purpose of the paper is not to promote either green or grey infrastructure solutions to CSOs or other urban environmental problems, but to highlight how local conditions shape apparently technical decisions about urban water infrastructure.

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4 The paper aims to highlight the complexity of local environmental and institutional  
5 conditions that shape decisions about urban water infrastructure, in this case the response  
6 to CSOs. The revisions have aimed to highlight the range of specific factors that influence  
7 decisions in each case, rather than to identify opportunities or barriers to transferring  
8 technologies or regulatory approaches between different countries. The political nature of  
9 decisions about infrastructure is evident in how different interests and institutional  
10 frameworks lead to particular outcomes.  
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For Peer Review Only

## Introduction

Combined Sewer Overflows (CSOs) are a significant environmental problem for many cities, which is compounded by sewerage infrastructure constructed in the nineteenth and early twentieth centuries. The issue here is that combined sewers drain both wastewater and surface water into water-based sanitation systems before being released into the environment. (Bazalgette, 1865; Beder, 1989; Halliday, 2001; Melosi, 2000). As part of this, the combined system integrated CSOs in order to prevent sewer flooding during high rainfall events by discharging peak flows directly into local rivers. The problem is that these discharges have generally increased in frequency since the systems were first installed. Surface water runoff to sewers has increased because urban surfaces have become more impermeable due to paving and development and because base-flows of wastewater in sewers have increased due to higher water consumption. This has led to a situation where the frequency of CSOs has become a significant barrier to improving water quality in many major urban rivers around the world.

While the fundamental cause of CSOs may be similar in cities with similar sewerage systems, responses to the problem vary greatly. 'Green' infrastructure solutions focus on source control of surface water, using techniques such as green roofs, rain gardens, detention basins and infiltration, to prevent or delay runoff into the sewers. 'Grey' infrastructure solutions adapt or expand conventional sewerage networks, including interceptor tunnels to collect CSO discharges before the contaminated water enters the 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'

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3 infrastructure is often presented as the progressive, sustainable option, while 'grey'  
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5 infrastructure represents a secure continuation of conventional sewerage design and  
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7 management.  
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12 Interest and adoption of "green" stormwater management approaches is a relatively recent  
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14 phenomenon. During the 1970s the negative impact of CSOs became the focus of  
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16 environmental campaigning and government regulation in the US and UK (Karvonen, 2011;  
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18 Novotny et al., 2010). Since then, engineers and urban designers have been developing a  
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20 range of techniques for managing stormwater at its source in order to reduce the level of  
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22 urban runoff entering the sewer system. These policies and techniques are variously known  
23  
24 as Best Management Practices (BMPs), Low Impact Development (LID) practices, Water  
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26 Sensitive Urban Design (WSUD), Sustainable (Urban) Drainage Systems (SuDS), and Green  
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28 Infrastructure.  
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37 Trends towards more localised management of stormwater are seen by some as part of a  
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39 long-term trend towards more sustainable cities. Novotny et al. (2010) identify 5 paradigms  
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41 of urban water management starting with the construction of sewers and moving to the  
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43 focus on sustainable cities. Brown et al. (2009) trace the movement from a drained city  
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45 towards the future water sensitive city in Australia. While there is evidence of increasing  
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47 application of green infrastructure, as we will see, this is not a universal phenomenon.  
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55 This paper analyses four case studies of cities from the United States and the United  
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57 Kingdom responding to CSOs with different combinations of green and grey infrastructure.  
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59 London's Tideway Tunnel project will construct a 30km-intercepting sewer underneath the  
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3 River Thames and expand sewage treatment works. Philadelphia is pursuing a strategy  
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5 entirely based on green infrastructure and source control of surface water runoff. Glasgow  
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7 and Washington DC are implementing hybrid strategies combining both green and grey  
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9 solutions to prevent CSOs. The case studies demonstrate the complexity of decisions in  
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11 developing strategies for CSO prevention. Factors that emerge as significant in shaping  
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13 decisions about CSOs include environmental regulation, infrastructure ownership and  
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15 governance, local leadership and the biophysical environment. The purpose of the paper is  
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17 not to promote green or grey infrastructure solutions to CSOs or other urban environmental  
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19 problems, but to highlight how local conditions shape apparently technical decisions about  
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21 urban water infrastructure. The paper begins with a summary of key legislation driving  
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23 environmental actions in the US, England and Scotland, before analysing the problem and  
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25 solution to CSOs in each city and finally comparing key factors that shape the particular local  
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27 responses to a common problem.  
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### 40 **Legal frameworks**

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42 The recognition of CSOs as a problem requiring attention and the drivers for action is in part  
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44 a result of environmental legislation. The legal frameworks, created by municipal, state,  
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46 national, and international regulation and administration, underpin the responses from  
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48 cities in the US and the UK. In England and Scotland the EU Urban Waste Water Treatment  
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50 (UWWT) Directive of 1991 required states to institute secondary treatment of domestic and  
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52 mixed wastewater discharges in settlements of more than 2,000 people, and tertiary  
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54 treatment of wastewater from larger towns and cities in sensitive areas.<sup>1</sup> The EU Water  
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<sup>1</sup> 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.

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3 Framework Directive in 2000 expanded wastewater management to include river basin  
4 management. The goal being to achieve 'good status' for all freshwater ecosystems and  
5 water bodies by 2015, followed by a second round of plans for 2015-2021. The  
6 Environmental Agency (EA) and the Scottish Environment Protection Agency (SEPA) are  
7 responsible for river basin management planning and the enforcement of water quality  
8 standards in England and Scotland respectively. It is worth stressing that while all regions of  
9 the UK have enacted legislation designed to promote the use of SuDS in new developments;  
10 guidance through the planning process has been considerably stronger in Scotland than  
11 England (MWH, 2011; ENW, 2013).  
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28 In the United States, the core piece of legislation is the 1972 Clean Water Act (CWA) which  
29 set a goal that all public waterways should be fishable and swimmable by 1985 (US EPA,  
30 2013; US EPA, 2014a). Despite considerable progress, by the early 1990s over one-third of  
31 America's assessed waterways still failed to meet federal water quality standards. In  
32 response, the federal Environmental Protection Agency (EPA) established a more stringent  
33 regime in the 1994 National Pollutant Discharge Elimination System (NPDES) permit  
34 programme. Among other steps, the NPDES mandated that regulated municipalities had to  
35 create and implement Long Term Control Plans (LTCPs), in which a schedule of selected CSO  
36 controls had to be set. Municipalities that fail to adequately control CSOs face legal and  
37 financial consequences and can be forced to comply with a consent decree — a legally  
38 binding agreement for the control of discharge waters. Since the implementation of the  
39 NPDES, the EPA has increasingly clarified and supported the use of LID in meeting  
40 stormwater requirements. This has led to a small but growing trend amongst cities to begin  
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3 writing or reopening consent decrees to include significant green infrastructure components  
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5 (Stoner, 2011; EPA, 2014c).  
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## 10 **London**

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12 Greater London is a city of over 8.6 million people, covering 1,572 square kilometres. It is  
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14 situated on the tidal reach of the River Thames and has an annual average rainfall of  
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16 640mm. London's combined sewerage system is a famous exemplar of nineteenth century  
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18 engineering (Halliday, 2001). The combined sewer system was originally designed to  
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20 overflow into the Thames on average four times per year, but CSOs now occur in London  
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22 more than 50 times per year on average (Bazalgette, 1865; Thames Water, 2012). In 2012,  
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24 this situation led the European Court of Justice to rule that the UK was in breach of the  
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26 UWWT Directive in relation to CSOs in London.  
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36 London's existing sewerage infrastructure is owned and operated by a private company,  
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38 Thames Water Utilities Ltd (Thames Water). The Office of Water Services (Ofwat) regulates  
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40 investment, pricing, and other business operations, while the Environment Agency (EA)  
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42 regulates abstraction licencing, discharge permits, flood protection and other environmental  
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44 activities.  
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52 In 2000 Thames Water commissioned the Thames Tideway Strategic Study (TTSS) to set  
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54 objectives and evaluate options for 'protecting the Thames Tideway from the adverse  
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56 effects of wastewater discharges' (TTSS, 2005, p.5). It was overseen by a steering  
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58 committee, chaired by independent engineer Chris Binnie, and included representatives of  
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3 the EA, the Department of Environment, Food and Rural Affairs (Defra), the Greater London  
4 Authority and Thames Water, with Ofwat holding an observer role. SuDS and source control  
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6 measures were investigated and rejected by the TTSS because of the highly urbanised  
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8 nature of the catchment, excessive costs, the impermeability of London's clay soils, and the  
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10 absence of natural receiving waters (due to the incorporation of many of London's original  
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12 streams and rivers into the sewerage network). The final recommendation of the TTSS was  
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14 that a 35km interceptor tunnel should be built from Hammersmith in west London to the  
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16 Crossness Sewerage Treatment Works in the Thames Estuary. The estimated cost of the  
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18 tunnel was £1.7 billion at 2004 prices. The proposal was refined to prioritise CSOs in the  
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20 River Lee by constructing a separate Lee Tunnel. This reduced the length of the Tideway  
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22 Tunnel to 30km, with discharge and treatment at Beckton, the site of existing wastewater  
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24 treatment works in the east of London. In 2006, Ofwat commissioned a review of the TTSS  
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26 study by consultancy firm Jacobs Babtie. The report proposed an alternative strategy of  
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28 integrated stormwater management, including SuDS, two shorter tunnels, separation and  
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30 real time control of stormwater in sewers, and in-river treatment. This proposal was  
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32 rejected on the basis that it would not deliver the require reductions in CSOs to meet  
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34 UWWT Directive requirements.  
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In 2011 the Thames Tunnel Commission (TTC), funded by five London local authorities most impacted by the tunnel construction, called for a re-evaluation of alternatives, including 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

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3 States Natural Resources Defense Council, and Frans H.M. van de Ven, leader of the Urban  
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5 Land and Water Management team at the Dutch independent institute for delta technology  
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7 (Deltares). Submission to the TTC came from local authorities, residents and environmental  
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9 groups, individual experts and citizens, Thames Water and the relevant regulators and  
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11 government authorities.  
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18 One of the key issues addressed by the report of the TTC was the environmental objective  
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20 set by the TTSS to address the problem of CSOs in London. In the absence of specific  
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22 regulatory standards for urban water quality, the TTCC chose standards to support specific  
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24 fish species, using dissolved oxygen concentration as a key indicator, as well as public health  
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26 risk and aesthetic considerations. According to the TTC setting such high environmental  
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28 standards underpinned the selection of the tunnel as the only viable solution, despite high  
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30 cost. Alternative strategies, including green infrastructure or a smaller tunnel, were  
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32 undermined by the difficulty of achieving such 'unrealistic' water quality standards (TTC  
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34 2011, p. 11). Other issues raised by the TTC against the Tideway Tunnel included questioning  
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36 forecasts of increasing wastewater baseflow in sewers and the rationale for objectives to  
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38 achieve improved water quality standards in a relatively short time scale. The TTC  
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40 highlighted the multiple benefits of GI compared with the single function of the tunnel as a  
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42 solution to CSOs. The TTC noted that the governance and administrative structures for  
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44 managing water in London undermined efforts towards integrated urban water  
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46 management:  
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56 There is a need to address current planning and funding arrangements for water and  
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58 wastewater systems, as under these it is easier to construct large, costly, inflexible  
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60 and environmentally impacting infrastructure systems, like the tunnel, than it is to

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3 provide green infrastructure alternatives that deliver many benefits to society and  
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5 that are adaptable to a changing climate (TTC 2011, p. 3).  
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11 In 2013 the Environment Agency (EA) undertook a review to answer the question 'Do we  
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13 have sufficient evidence and knowledge to be confident that Sustainable Drainage Systems  
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15 (SuDS) could or could not be reasonably implemented at a scale that achieves the water  
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17 quality standards for the tidal Thames?' (EA 2013, 3). The report concluded that SuDS alone  
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19 could not meet UWWTD standards and that the costs, benefits and timeliness of SuDS  
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21 retrofitting were highly uncertain compared with the tunnel. The EA report highlighted  
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23 complex institutional arrangements as a barrier to SuDS implementation, referring to a 2011  
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25 Ofwat report which compared arrangements for surface water management in England and  
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27 Wales to other countries (MWH 2011).  
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36 In 2014 Chris Binnie, the original chair of the TTSS steering group, published an independent  
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38 report opposing the Tideway Tunnel. Binnie claimed that many of the improvements  
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40 needed to reach the original objectives of the TTSS had been achieved through the  
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42 construction of the Lee Tunnel and the associated improvements at sewage treatment  
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44 works, and that implementation of SuDS could significantly reduce storm flows into the  
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46 sewers. His change of assessment was based on developments in design, data and  
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48 modelling of SuDS that were not available at the time of the TTSS analysis, and on a  
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50 reconsideration of assumption about growth in wastewater base flows. Binnie was  
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52 particularly critical of the revised cost estimates for the tunnel, which by 2014 had risen to  
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54 £4.1 billion, compared to the original TTSS estimate of £1.7 billion in 2004. In 2005 the  
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estimated annual increase in Thames Water customers' bills was £40, compared a maximum of £80 in 2015.

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 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 since received attention in London as a strategy for surface water management, as a method to relieve pressure on sewers in catchments with limited additional capacity, and for flood resilience. One example is 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 utilise SuDS in particular catchments to address sewer capacity constraints and surface water flooding. Most Local Authorities now recommend SuDS through the development planning process, but enforcement is constrained by the lack of implementation of national policy relating to SuDS and new developments. Thus, while the Tideway Tunnel remains the solution to CSOs, green infrastructure is starting to be promoted for its wider benefits to drainage, flooding and the urban environment.

### **Glasgow**

The City of Glasgow has a population of approximately 606,000 residents with the wider Glasgow and Clyde Valley metropolitan region having a population of just over 1.5 million. 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

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3 network between 1850 and 1875 in conjunction with the building of its underground  
4 system. Under the direction of the Glasgow Corporation, over 80 kilometres of pipe were  
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6 laid to help address pollution and sanitary problems that plagued the city as a result of rapid  
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8 industrialisation, population growth and the existing system of open sewers. The system  
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10 was built using a series of intercepting sewers (some based on culverting existing  
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12 watercourses) that gathered wastewater to be processed at one of three newly constructed  
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14 wastewater treatment facilities (Dalmarnock, Dalmuir, and Shieldhall), and then discharged  
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16 into the River Clyde. Glasgow's sewers combine surface and wastewater, and as a result of  
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18 CSOs the River Clyde and many of its surrounding watercourses have been classified as  
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20 having 'poor' quality waters according the EU Water Framework Directive.  
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31 In response to a major flooding event in 2002, which saw raw sewage deposited in the  
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33 streets and basements of the city, and the imperatives of implementing the EU Water  
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35 Framework Directive, Glasgow created the 'Glasgow Strategic Drainage Plan – a  
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37 comprehensive assessment of drainage needs across Glasgow and the surrounding towns'  
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39 (Adshead 2002, 1). To create this plan and address the city's legacy position of decaying  
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41 sewers and lack of investment, the city commissioned Hyder Consulting to bring together  
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43 'key stakeholders' including Scottish Water, Glasgow City Council, Scottish Environment  
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45 Protection Agency (SEPA), Scottish Enterprise Glasgow, and subsequently Scottish Water  
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47 Solutions (a consortium of Scottish Water, other water companies and engineering  
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49 contractors). The goal of this partnership was not simply to look at gray solutions but to  
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51 actively promote and find green possibilities to addressing (or helping to address) any future  
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53 flooding.  
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4 The partnership approach that brought together stakeholders and agencies launched with  
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6 the development of the Drainage Plan was carried forward with the formation of the  
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8 Glasgow Strategic Drainage Partnership, later expanded and renamed Metropolitan  
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10 Glasgow Strategic Drainage Partnership (MGSDP). This partnership, led by the Glasgow City  
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12 Council, brought together relevant local authorities including SEPA, Scottish Water, Scottish  
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14 Enterprise and British Waterways Scotland (which manages Scottish Canals under contract  
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16 from the Scottish government). The purpose of the partnership is to find ways to 'upgrade  
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18 and modernise Glasgow's drainage and sewerage network to reduce flooding and support  
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20 urban development requirements, while improving water quality and the environment'  
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22 (MGSDP 2008, 1).  
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31 The role of SuDS in managing urban surface water was entrenched in this process by the  
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33 Water Environment and Water Services (Scotland) Act (2003) (and its subsequent  
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35 amendments), which redefined the term 'sewer' to include SuDS and made Scottish Water  
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37 responsible for maintenance and replacement of all shared public SuDS. While all parties  
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39 have a role to play in the development and implementation of SuDS, and the Scottish  
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41 Government and SEPA encourage all developers to consider the use of SuDS when  
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43 retrofitting buildings and properties. One of the shortfalls of the 2003 Act is that it only  
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45 requires Scottish Water to adopt approved SuDS systems, which have been integrated into  
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47 new developments. Retrofits and non-approved systems remain outside the remit of the  
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49 Act.  
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58 Having a requirement for the integration of SuDS in all new developments, Glasgow has  
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60 seen a considerable range of SuDS projects completed over the past few years. One of the

1  
2  
3 largest is designed to reduce the effects of storm flooding in South Glasgow. The  
4  
5  
6 neighbourhoods of East Renfrewshire, Kirkland Bridge, Kittoch Bridge were selected for  
7  
8 SuDS redesign integrating 'flood storage areas...(which would) enhance biodiversity through  
9  
10 the creation of artificial wildlife habitats, the creation of woodlands, scrub (lands)... wet  
11  
12 grasslands, shallow scrapes, and ponds' (McGowan & Douglas 2014, 2). The project  
13  
14 attenuates the flow of the White Chart, Earn, and Kittoch rivers before their floodwaters  
15  
16 reached Glasgow. Significantly, this project was developed under the guidance of a working  
17  
18 group of SEPA, Scottish Natural Heritage, Scottish Water, local angling groups and fisheries,  
19  
20 RSPB, representatives from three local authorities, and involved active public consultation.  
21  
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28 While green infrastructure is an element of Glasgow's stormwater plan, the core of Scottish  
29  
30 Water's development plan is the construction of several large storage and conveyance  
31  
32 tunnels under the city, the largest of which is a three-mile tunnel to run from Queen's Park  
33  
34 to Craigton industrial estate. Scottish Water describes the £100 million project as:  
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41 The biggest investment in the network since Victorian times, the upgrade will  
42  
43 improve river water quality and the natural environment of the River Clyde and its  
44  
45 tributaries, enable the Greater Glasgow area to grow and develop, alleviate sewer  
46  
47 flooding and deal with the effects of increased rainfall and climate change. (Scottish  
48  
49 Water 2013)  
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56 The Scottish Water preference for ponds, basins and large-scale underground storage  
57  
58 tunnels is in part due to existing urban infrastructure, soil type and variation in Glasgow's  
59  
60 average rainfall. Glasgow is built on a complex mix of soils including: wet mud and sand,



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3 boulder clay, solid rock, shale, sandstone, and quicksand. Monthly average rainfall ranges  
4  
5 from highs of 130-140mm in December and January to lows of 60-65mm per month  
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7  
8 between April and June. As such, while SUDS are recommended or required in many  
9  
10 documents, the primary techniques tend not to include infiltration and site-specific  
11  
12 practices (as commonly found in the US).  
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16  
17 While there is widespread political and industrial support for the implementation and use of  
18  
19 SuDS in Scotland, a 2013 report by consulting firm Hydro, 'Engineering Nature's Way', found  
20  
21 that of the 151 respondents working in local authorities, SEPA, consulting, homebuilding,  
22  
23 contracting and other sectors, 45% felt that SuDS had only been 'somewhat successful'. This  
24  
25 view was explained to be the result of, 'the constraints put in place by Scottish Water and  
26  
27 the Local Council as to what they are willing to adopt makes it difficult to use the full range  
28  
29 of SuDS features'. More than 84% of respondents believed that more could be done to  
30  
31 advance the retrofitting of SuDS in urban areas. One homebuilder noted: 'Whilst there is  
32  
33 attention being paid to flood prevention in these areas, very little is being done regarding  
34  
35 SuDS'. The problem associated with retrofitting was a belief (held by over 75% of  
36  
37 respondents across all sectors) that there was inadequate funding for the adoption and  
38  
39 maintenance of SuDS when considering solutions. On a positive note, as has occurred in  
40  
41 London, as a result of the efforts to use SuDS in the control of wastewater entering the Rive  
42  
43 Clyde both salmon and sea trout have begun to repopulate the lower Clyde.  
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## 54 55 56 **Washington DC**

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58 Washington DC has a population of over 600,000 residents and occupies 158 square  
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60 kilometres at the confluence of the Anacostia and Potomac Rivers. DC has an average

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2  
3 rainfall of 1,160mm and sits in the heart of the Chesapeake Bay watershed, which is  
4  
5 currently threatened by hypoxia and eutrophication, despite significant efforts by DC and  
6  
7 other watershed stakeholders to address the situation (Boesch et al. 2001; Chesapeake Bay  
8  
9 Program, 1987; National Research Council 2008).  
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15 As the capital city, DC has operated under direct federal control or oversight and the federal  
16  
17 government owns 40% of land, including much of that immediately adjacent to the district's  
18  
19 major water bodies (Chesapeake Bay Program 1996). The District of Columbia Water and  
20  
21 Sewer Authority (DC Water) manages combined sewers and the Blue Plains sewage  
22  
23 treatment plant and its finances are not tied to DC's overall budget (DC Water 2012b; DC  
24  
25 Water n.d.). The District of Columbia Department of the Environment (DDOE) is also  
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27 integrally involved through management of separate storm sewers and the management  
28  
29 and regulation of DC's waters.  
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38 DC's over 60 CSO outfalls (triggered by rain events as little as 2.5mm) continue to be a major  
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40 source of impairment for receiving waters (DC Water 2002). In response to legal suits for  
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42 Clean Water Act Violations, and under a 2005 consent decree, DC Water created the 'Clean  
43  
44 Rivers Project,' Long Term Control Plan (LTCP) (US District Court for DC 2003). This plan is  
45  
46 designed to reduce CSO overflow volumes in the city by 96% to an estimated 138 mg/avg yr  
47  
48 at an estimated cost of \$2.6 Billion (2001 dollars) (DC Water, 2012b; DC Water, 2014b). The  
49  
50 plan originally featured the creation of four storage and conveyance tunnels and \$3 million  
51  
52 devoted to LID retrofits, largely in the form of demonstration projects (DC Water 2012b).  
53  
54 Reasons the initial plan did not include more GI are: lack of information; the high rate of  
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56 CSO reductions required; and short timetable for improvements (Ray 2014). The last two  
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3 considerations were particularly acute in DC, perhaps because of DC's location in the  
4 sensitive and polluted Chesapeake Bay watershed.  
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10 While grey infrastructure was a component of DC Water's original LTCP, other city agencies  
11 have encouraged the use of green infrastructure through a variety of policy and planning  
12 instruments, designed to address broader water quality issues. For instance, DDOE's  
13 RiverSmart Homes program provides consultation and subsidies to property owners for  
14 onsite stormwater management (DDOE ndb). In 2010 DDOE and DC Water began to assess  
15 stormwater removal fees tiered to impervious area (DDOE, ndc; DC Water nde). In 2013  
16 DDOE released guidelines requiring all new construction greater than 465 square metres to  
17 retain the first 30mm of rainfall or to combine on-site and off-site retention through their  
18 Stormwater Credit Trading programme (DDOE 2013). In 2013, the DC Department of  
19 Planning instituted the Green Area Ratio, a planning instrument that requires all new  
20 development and significant renovation projects to incorporate green landscape elements  
21 (DDOE 2014).  
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43 Several converging trends led to the reopening of DC's consent decree in 2014 to include a  
44 significant green infrastructure requirement. First, a significant increase in information  
45 about green infrastructure related stormwater benefits and financial costs have emerged.  
46 In addition, the EPA has clarified and supported the role of green infrastructure in meeting  
47 regulatory requirements (Casey Trees). There were also changes in DC Water. Amongst  
48 these was the 2009 decision to hire George Hawkins as CEO and General Manager, a man  
49 with a background as an environmental advocate, director of the DDOE, and chair of the  
50 committee to develop DC's sustainability plan  
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3 (http://www.dewater.com/about/hawkins.cfm). Finally, around this time, the financial  
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5 implications of the current consent decree became increasingly clear. Of particular concern  
6  
7 was the effect of rising sewerage rates on low-income residents (DC Water 2014b; Ray  
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9 2014).

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16 In 2016, the *Long Term Control Plan Modification for Green Infrastructure* was officially  
17  
18 accepted. This plan fully replaces one of four newly planned CSO interceptor tunnels with a  
19  
20 green infrastructure investment of \$90 million, addresses overflows to the Potomac through  
21  
22 a combination of grey-green infrastructure, and gives the city an additional five years to  
23  
24 complete the project (DC Water 2014b). DC Water justifies this change citing added social,  
25  
26 environmental and economic benefits, reduced financial impact on ratepayers, and synergy  
27  
28 with the Mayor's Sustainable DC Plan (DC Water 2014b; DDOE nd). While community and  
29  
30 advocacy groups generally support the inclusion of green infrastructure, concerns about the  
31  
32 plan have also been articulated. These include: 1) the effects/necessity of delays in the  
33  
34 timetable relative to the initial LTCP; 2) accountability being tied to budget spent on green  
35  
36 infrastructure rather than environmental outcomes; 3) insufficiently articulated  
37  
38 maintenance and repair costs and protocols, and 4) the unfortunate clustering of green  
39  
40 infrastructure projects within the city—significantly *not* occurring in some of the poorest  
41  
42 communities neighbouring the Anacostia River (NRDC, nd; Chavez, 2014; Fellows, 2014).  
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### 53 Philadelphia

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55 Philadelphia is the sixth largest US city, with a population of over 1.5 million (down from a  
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57 peak of 2 Million in the 1950s) occupying 347 square kilometres. Despite high levels of  
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59 poverty (26%), in many ways Philadelphia has been a pioneer in water management. It was  
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1  
2  
3 the first US city to take on water supply as a municipal responsibility in 1801 and later  
4  
5 created the 45-hectare Fairmount Park in the middle of the city to protect the city's water  
6  
7 supply (City of Philadelphia nd). The Philadelphia Water Department (PWD) was created in  
8  
9 the 1950s as a municipally owned and financed department, to manage drinking water and  
10  
11 wastewater services. Currently, the PWD maintains three wastewater treatment plants and  
12  
13 nearly 4,828 km of sewers (60% of which are combined) within the city and neighbouring  
14  
15 596 square km of suburbs (Holst 2007). Philadelphia receives about 1,043 mm of  
16  
17 precipitation per year and has well-drained soils, yet—due to development on historic tidal  
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19 marsh—experiences flooding and subsidence in some areas (PWD 2009).  
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28 Several developments paved the way for Philadelphia's current approach to stormwater  
29  
30 management. First, the region has been influenced by planning and landscape practitioners  
31  
32 who trained with The University of Pennsylvania's Ian McHarg (raised in Glasgow), whose  
33  
34 1969 book *Design with Nature* is the cornerstone text developing the concept of ecological  
35  
36 planning. Second, de-industrialisation challenges, particularly abandoned properties and  
37  
38 vacant lots have galvanised and unified many non-profit organisations and city agencies for  
39  
40 over 20 years (Pennsylvania Horticultural Society 1995; City of Philadelphia nd). Third, PWD  
41  
42 has a long history of thinking of land-water interconnections within its system and of  
43  
44 regional watershed management. Led by Howard Neukrug, the PWD developed the Office  
45  
46 of Watersheds in 1999 to better address the formerly separate operations of CSO  
47  
48 management, stormwater management and source water control watershed-wide (PWD  
49  
50 2009). Crucially, that Office defined its mission broadly, stating, 'government agencies  
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52 (must) break out of their traditional roles of providing narrowly defined services' (City of  
53  
54 Philadelphia 2011).  
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6 In order to comply with the federal Clean Water Act, PWD first examined the costs and  
7  
8 benefits of various CSO management options utilising a 'Triple Bottom Line' assessment  
9  
10 methodology (Stratus Consulting 2009). This approach compared costs of potential projects  
11  
12 that included an assessment of wider social, economic and environmental benefits of each  
13  
14 option. In this report, green infrastructure compared favourably to grey alternatives  
15  
16 primarily due to non-water-related benefits including reductions in heat-stress mortality,  
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18 improved aesthetics and property value, and increased recreational opportunities  
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20 (Maimone et al. 2011).  
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29 Based on these findings, in 2009, the PWD created the Long Term Control Plan: 'the single  
30  
31 largest investment in the City's environment over the next 25 years...presents a unique  
32  
33 opportunity to be much more than just a water quality improvement program.'  
34  
35 Philadelphia's 'Green City, Clean Waters' plan sets out an agenda spending \$2.4 billion  
36  
37 between 2011-2026, 67% of which will be spent on green infrastructure techniques  
38  
39 (DeGood 2013). This is a commitment to reshape the city (US Housing and Urban  
40  
41 Development 2013) by developing 'the most extensive urban network of green  
42  
43 infrastructure in the United States', and using Philadelphia's vacant land as a resource  
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45 (Natural Resources Defense Council nd).  
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54 This plan was formalised through a Consent Decree and Partnership Agreements with the  
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56 EPA and state authorities (EPA 2015). The objective, create 9,500 'Greened Acres' over 25  
57  
58 years. That is, to convert nearly 40.5 km<sup>2</sup> of impermeable surfaces to manage 25mm of  
59  
60 runoff onsite and reduce overflows by 85% through projects on both public and private

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3 property (Maimone et al. 2011; Water Environment Federation 2014). The city owns  
4  
5 approximately 45% of impervious surfaces within the CSO area and will integrate green  
6  
7 infrastructure into capital improvement projects on city-owned streets, sidewalks, and  
8  
9 properties. Other public land projects include a large-scale street tree planting programme;  
10  
11 preserved open space—including dedication of vacant and abandoned lands, and stream  
12  
13 restoration (City of Philadelphia 2011; US Housing and Urban Development 2013).  
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20 The PWD has created requirements and incentives for green stormwater management on  
21  
22 private property; including rain gardens, green roofs, street trees, porous pavers, and other  
23  
24 green interventions. Beginning in 2010, the PWD adopted a parcel-based billing system for  
25  
26 commercial properties. These assess fees in proportion to the amount of impervious  
27  
28 surface. A geographical information system (GIS) supports this programme so that property  
29  
30 owners can view information about their parcel's imperviousness online (Cunningham  
31  
32 2011). In addition to greater equitability, this system encourages green retrofits  
33  
34 (Valderrama et al. 2012). Grant programmes also provide technical and financial assistance  
35  
36 and encourage project aggregation for commercial property owners (Valderrama et al.  
37  
38 2013; PWD 2015). As of June 2014—five years into the 25-year planning period—the city  
39  
40 had created 1.3 km<sup>2</sup> of newly pervious area (City of Philadelphia 2014).  
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## 51 Discussion

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53 Comparing different responses to CSOs in four cities reveals key factors influencing urban  
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55 environmental decision-making, summarised in Table 1.  
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Table 1. Comparing responses to Combined Sewer Overflows in Four Cities

	London	Glasgow	Washington DC	Philadelphia
<b>Environment</b>	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.
<b>Regulation</b>	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.
<b>Governance</b>	Private ownership of infrastructure. EU Directives. Local government jurisdiction uncertain.	Public ownership of infrastructure via Scottish Water. EU Directives. Range of Scottish Acts and building regulations.	DC water is independent authority of DC. DDOE manages MS4s and responsible for receiving water quality. Federal ownership of 40% of land area.	PWD is municipally owned and financed.
<b>Economics</b>	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.
<b>Society</b>	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.
<b>Leadership</b>	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.

Local environmental conditions such as rainfall, receiving water quality, soil type, climate change forecasts and urban density influence the technical feasibility of different options.

For instance, London's clay soils and high density urban form were a point of contention as



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4 proponents of the tunnel claimed that they constrained opportunities for infiltration and  
5  
6 local storage of stormwater, while Philadelphia's well drained soils and areas of abandoned  
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8 land made green infrastructure solutions more feasible. Opponents of the Tideway Tunnel  
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10 in London contested the high environmental objectives set by the Thames Tideway Strategic  
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12 Study as leading to an unnecessarily high cost solution focussed only on water quality to the  
13  
14 detriment of wider environmental benefits of green infrastructure.  
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21 The governance of urban drainage infrastructure, including ownership, planning and  
22  
23 regulation, influences decision making about responses to CSOs. London was unique of the  
24  
25 four case study cities in that its drainage, sewerage and wastewater infrastructure are  
26  
27 privately owned. The decision-making process in London involved a range of stakeholders  
28  
29 and was highly scrutinised by government agencies and independent regulators. However,  
30  
31 the separation between privately owned infrastructure and public responsibility for urban  
32  
33 planning in London is less conducive to institutional integration and flexibility, which was  
34  
35 evident in cities such as Glasgow that placed greater emphasis on green infrastructure  
36  
37 solutions. Municipally focused responses to CSOs in the two US based case studies enabled  
38  
39 the implementation of a wider range of planning and regulatory instruments to promote  
40  
41 green infrastructure than in the UK cases, especially London. Philadelphia, the only city in  
42  
43 our sample to focus entirely on green infrastructure, chose this option primarily based on  
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45 assessments of the non-water benefits to their community. Crucially, its public water  
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47 department was able to define its mission broadly, breaking with traditions of more  
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49 narrowly defined service provision.  
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3 While both the UK and US have regulations surrounding CSO abatement, this is another  
4 point of difference. In the US, there is intense legal pressure to manage CSOs, through the  
5 development of legally binding Long Term Control Plans. While these plans are required, the  
6 approach to CSO abatement is not proscribed. The regulatory environment in the US is  
7 increasingly open to green infrastructure, but most US cities have implemented LTCPs  
8 emphasizing “grey” infrastructure strategies, only setting aside small funds for LID  
9 demonstration projects. In this context, DC is now a part of a small but growing number of  
10 US cities to integrate green infrastructure more substantively into its LTCP, and Philadelphia  
11 is the only US city we are aware of that has utilized a CSO abatement approach based  
12 primarily on green infrastructure.  
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30 The economic context of each city and the ownership of its infrastructure influenced the  
31 viability of different options for reducing CSOs. Private ownership, secure income through  
32 regulated water charging, and central government underwriting as a project of national  
33 importance, provide a structure for capital investment for the interceptor tunnel in London.  
34 By contrast, municipal governments in DC and Philadelphia are highly constrained in their  
35 ability to raise capital and increase sewer charges, providing a driver for less capital-  
36 intensive green infrastructure solutions.  
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50 Social drivers in decision-making about drainage are evident in the integration of green  
51 infrastructure into urban regeneration planning for post-industrial Glasgow and  
52 Philadelphia. Environmental justice concerns about the impact of CSOs on poor  
53 neighbourhoods compared to the benefits of green infrastructure in wealthier  
54 neighbourhoods have shaped debate in Washington DC. Social engagement in London has  
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3 mostly been limited to protests by residents and local politicians in boroughs most impacted  
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6 by the construction of the tunnel, and support by recreational users of the river.  
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11 The role of strong local leaders in making the case for green infrastructure solutions was  
12  
13 evident in Philadelphia, Washington DC, and Glasgow but notably absent in London. In  
14  
15 London the main proponents of SuDS solutions were outside Thames Water and key  
16  
17 regulators and decision makers, and were therefore positioned as opponents to the tunnel.  
18  
19 In Glasgow and the US cities, strong individual leaders within the water utilities and city  
20  
21 government were able to demonstrate the wider values of green infrastructure and achieve  
22  
23 change across institutions by linking to broader environmental and sustainability objectives  
24  
25 despite some uncertainty about green infrastructure implementation at scale and related  
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27 costs, including maintenance.  
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### 36 **Conclusion**

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38 Combined sewers represented a standard engineering response to nineteenth century  
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40 public health crises, but responses to the problem of CSOs in the twenty-first century are  
41  
42 more divergent. In the US, legal action is requiring cities to rapidly address CSO problems  
43  
44 through the development of long term control plans, some of which include green  
45  
46 infrastructure solutions. Local environmental, economic, political and social conditions are  
47  
48 shaping technical decisions about how to solve CSOs. Comparing London, Glasgow,  
49  
50 Washington DC and Philadelphia shows that the choice of 'green' or 'grey' solutions is highly  
51  
52 dependent on diverse factors such as access to capital investment, institutional flexibility,  
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54 local leadership regulatory frameworks, and urban social context. Technical constraints also  
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56 contribute to grey and green infrastructure choice.  
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7 As post-industrial cities follow different economic, social and political pathways, their  
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9 infrastructural choices are also diverging. Green infrastructure solutions are more viable in  
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11 Glasgow, Washington DC and Philadelphia where drainage infrastructure is still publically  
12  
13 owned and a wider range of policy instruments are used to promote sustainable and  
14  
15 decentralised solutions. An interceptor tunnel was more viable in London where the  
16  
17 institutional, economic and regulatory structure of the water industry supported large  
18  
19 capital investment. While proponents of green infrastructure frame these solutions within  
20  
21 narratives of progress towards urban sustainability, the complexity of urban development  
22  
23 and infrastructure governance means that this may not be the next paradigmatic, universal  
24  
25 response to urban drainage challenges.  
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## Retrofitting urban drainage infrastructure: green or grey?

### Introduction

Combined Sewer Overflows (CSOs) are a threat to environmental health in many cities with drainage networks established in the nineteenth and twentieth centuries. The reason for this is that combined sewers transfer both surface and wastewater in a single pipe and are designed to overflow during heavy precipitation events, resulting in sewage discharge to waterways. Urban development reduces the permeability of land surfaces; as a result, cities have seen an increase in runoff and sewer overflows. Population growth also increases the base load of wastewater, further reducing the stormwater capacity of sewers. As such, finding ways to reduce CSOs is a high priority for environmental regulators around the world.

Responses to the problem of CSOs in different cities can be broadly characterised as 'green' or 'grey' infrastructure solutions or a hybrid of the two. More traditional 'grey' solutions are based on expanding the capacity of existing drainage systems, storing stormwater in large underground tanks and/or tunnels during the event. 'Green' infrastructure refers to a combination of decentralised measures to reduce runoff, increase biodiversity and improve urban environments by capturing water onsite. Examples include green roofs, rainwater harvesting, rain gardens, ponds, swales and bio-retention basins. The mix of grey and green infrastructure depends greatly on the local environmental, economic, institutional and social contexts.

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3 This paper explores the approaches that London, Glasgow, Washington DC and Philadelphia  
4 have taken in responding to urban stormwater and CSOs challenges. In brief, London has  
5 begun construction of a large interceptor tunnel with relatively little attention yet paid to  
6 green infrastructure, Philadelphia is pursuing green infrastructure based approaches, and  
7 Washington DC and Glasgow are implementing a combination of solutions. The cases  
8 illustrate that a diversity of responses are emerging to a common environmental problem in  
9 cities around the world.  
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### 23 **Trends in urban drainage**

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28 In the nineteenth century, combining surface water and wastewater into one set of pipes  
29 was economically and logistically preferable to building separate sewers (Bazalgette, 1865;  
30 Beder, 1989; Halliday, 2001; Melosi, 2000). As such, CSOs became a standard design feature  
31 of sewer systems built in cities during that period.  
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41 During the 1970s the negative impact of stormwater discharge became the focus of  
42 environmental campaigning and government regulation in the US and UK (Karvonen, 2011;  
43 Novotny et al., 2010). Since then, engineers and urban designers have been developing a  
44 range of techniques for managing surface water at source in order to reduce the level of  
45 urban runoff entering the sewer system. These policies and techniques are variously known  
46 as Best Management Practices (BMPs), Low Impact Development (LID) practices, Water  
47 Sensitive Urban Design (WSUD) and Sustainable (Urban) Drainage Systems (SuDS).  
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3 Trends towards more localised management of surface water are seen by some as part of a  
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5 long-term trend towards more sustainable cities. Novotny et al. (2010) identify 5 paradigms  
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7 of urban water management starting with the construction of sewers and moving to the  
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9 focus on sustainable cities. Brown et al. (2009) trace the movement from a drained city  
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11 towards the future water sensitive city in Australia. While there is evidence of increasing  
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13 application of green infrastructure and other environmentally sustainable techniques, as we  
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15 will see, this is not a universal phenomena.  
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### 23 Legal frameworks

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28 In England and Scotland the EU Urban Waste Water Treatment (UWWT) Directive of 1991  
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30 required states to institute secondary treatment of domestic and mixed wastewater  
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32 discharges in settlements of more than 2,000 people, and tertiary treatment of wastewater  
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34 from larger towns and cities in sensitive areas.<sup>1</sup> The EU Water Framework Directive in 2000  
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36 expanded wastewater management to include river basin management. The goal was to  
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38 achieve 'good status' for all freshwater ecosystems and water bodies by 2015, followed by  
39  
40 a second round of plans for 2015-2021. The Environmental Agency (EA) and the Scottish  
41  
42 Environment Protection Agency (SEPA) are responsible for river basin management planning  
43  
44 and the enforcement of water quality standards in England and Scotland respectively. It is  
45  
46 worth stressing that while all regions of the UK have enacted legislation designed to  
47  
48 promote the use of SuDS in new developments; guidance through the planning process has  
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50 been considerably stronger in Scotland than England (MWH, 2011; ENW, 2013).  
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<sup>1</sup> 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.

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6 In the United States, the core piece of legislation is the 1972 Clean Water Act (CWA) which  
7  
8 set a goal that all public waterways should be fishable and swimmable by 1985 (US EPA,  
9  
10 2013; US EPA, 2014a). Despite considerable progress, by the early 1990s over one-third of  
11  
12 America's assessed waterways still failed to meet federal water quality standards. In  
13  
14 response, the federal Environmental Protection Agency (EPA) established a more stringent  
15  
16 regime in the 1994 National Pollutant Discharge Elimination System (NPDES) permit  
17  
18 programme. Among other steps, the NPDES mandated that regulated municipalities had to  
19  
20 create and implement Long Term Control Plans (LTCPs), in which a schedule of selected CSO  
21  
22 controls had to be set. Municipalities that fail to adequately control CSOs face legal and  
23  
24 financial consequences and can be forced to comply with a consent decree — a legally  
25  
26 binding agreement for the control of discharge waters. Since the implementation of the  
27  
28 NPDES, the EPA has increasingly clarified and supported the use of LID in meeting  
29  
30 stormwater requirements. This has led to a small but growing trend amongst cities to begin  
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32 writing or reopening consent decrees to include significant green infrastructure components  
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34 (Stoner, 2011; EPA, 2014c).  
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## 45 46 **London** 47 48 49 50

51 Greater London is a city of over 8.6 million people, covering 1,572 square kilometres. It is  
52  
53 situated on the tidal reach of the River Thames and has an annual average rainfall of  
54  
55 640mm. London's combined sewerage system is a famous exemplar of nineteenth century  
56  
57 engineering (Halliday, 2001). The combined sewer system was originally designed to  
58  
59 overflow into the Thames on average four times per/year, but CSOs now occur in London  
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3 more than 50 times per year on average (Bazalgette, 1865; Thames Water, 2012). In 2012,  
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5  
6 this situation led the European Court of Justice to rule that the UK was in breach of the  
7  
8 UWWT Directive in relation to CSOs in London.  
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11  
12 London's existing sewerage infrastructure is owned and operated by a private company,  
13  
14 Thames Water Utilities Ltd (Thames Water). Investment, pricing, and other business  
15  
16 operations are regulated by the Office of Water Services (Ofwat), while the Environment  
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18 Agency (EA) regulates abstraction licencing, discharge permits, flood protection and other  
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20 environmental activities.  
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### 28 *Stormwater Decision-making*

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32 In 2000 Thames Water commissioned the Thames Tideway Strategic Study (TTSS) to set  
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34 objectives and evaluate options for 'protecting the Thames Tideway from the adverse  
35  
36 effects of wastewater discharges' (TTSS, 2005, p.5). It was overseen by a steering  
37  
38 committee, chaired by independent engineer Chris Binnie, and included representatives of  
39  
40 the EA, the Department of Environment, Food and Rural Affairs (Defra), the Greater London  
41  
42 Authority and Thames Water, with Ofwat holding an observer role. SuDS and 'source  
43  
44 control' measures were investigated and rejected by the TTSS because of the highly  
45  
46 urbanised nature of the catchment, excessive costs, the impermeability of London's clay  
47  
48 soils, and the absence of natural receiving waters (due to the incorporation of many of  
49  
50 London's original streams and rivers into the sewerage network). The final recommendation  
51  
52 of the TTSS was that a 35km interceptor tunnel should be built from Hammersmith in west  
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54 London to the Crossness Sewerage Treatment Works in the Thames Estuary. The estimated  
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3 cost of the tunnel was £1.7 billion at 2004 prices. The proposal was refined to prioritise  
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5 CSOs in the River Lee by constructing a separate Lee Tunnel. This reduced the length of the  
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7 Tideway Tunnel to 30km, with discharge and treatment at Beckton, the site of existing  
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9 wastewater treatment works in the east of London.  
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16 In 2006, Ofwat commissioned a review of the TTSS study by consultancy firm Jacobs Babbie.  
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18 The report proposed an alternative strategy of integrated stormwater management,  
19  
20 including SuDS, two shorter tunnels, separation and real time control of stormwater in  
21  
22 sewers, and in-river treatment. This proposal was rejected on the basis that it would not  
23  
24 deliver the require reductions in CSOs to meet UWWT Directive requirements.  
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31 In 2011 the Thames Tunnel Commission (TTC), funded by five London local authorities most  
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33 impacted by the tunnel construction, called for a re-evaluation of alternatives, including  
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35 green infrastructure options, in combination with a smaller tunnel, or no tunnel. In 2014  
36  
37 Chris Binnie, the original chair of the TTSS steering group, published an independent report  
38  
39 opposing the Tideway Tunnel. Binnie claimed that many of the improvements needed to  
40  
41 reach the original objectives of the TTSS had been achieved through the construction of the  
42  
43 Lee Tunnel and the associated improvements at sewage treatment works, and that  
44  
45 implementation of SuDS could significantly reduce storm flows into the sewers. His change  
46  
47 of assessment was based on developments in design, data and modelling of SuDS that were  
48  
49 not available at the time of the TTSS analysis. Binnie was particularly critical of the revised  
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51 cost estimates for the tunnel, which by 2014 had risen to £4.1 billion, compared to the  
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53 original TTSS estimate of £1.7 billion in 2004. In 2005 the estimated annual increase in  
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55 Thames Water customers' bills was £40, compared a maximum of £80 in 2015.  
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6 In 2013 the Environment Agency (EA) undertook a review to answer the question ‘Do we  
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8 have sufficient evidence and knowledge to be confident that Sustainable Drainage Systems  
9  
10 (SuDS) could or could not be reasonably implemented at a scale that achieves the water  
11  
12 quality standards for the tidal Thames?’ (EA 2013, 3). The report concluded that SuDS alone  
13  
14 could not meet UWWTD standards and that the costs, benefits and timeliness of SuDS  
15  
16 retrofitting were highly uncertain compared with the tunnel. The EA report highlighted  
17  
18 complex institutional arrangements as a barrier to SuDS implementation, referring to a 2011  
19  
20 Ofwat report which compared arrangements for surface water management in England and  
21  
22 Wales to other countries (MWH 2011).  
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31 Planning permission for the Tideway Tunnel was granted in August 2014. In June 2015 a new  
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33 private company, Bazalgette Tunnels (operating as ‘Tideway’), was formed to construct and  
34  
35 deliver the tunnel, with investment risks underwritten by the Treasury. Contracts for  
36  
37 construction of four separate sections of the tunnel have been awarded and construction  
38  
39 began in 2016.  
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46 Despite this large-scale commitment to grey infrastructure, SuDS have since received  
47  
48 attention in London. One example is the London Sustainable Drainage Action Plan, produced  
49  
50 in partnership between the Mayor of London, Thames Water, Tideway, London Councils and  
51  
52 the EA (GLA, 2015). Thames Water utilise SuDS in particular catchments to address sewer  
53  
54 capacity constraints and surface water flooding. Most Local Authorities now require SuDS  
55  
56 through the development planning process. Thus, while the Tideway Tunnel remains the  
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3 solution to CSOs, green infrastructure is starting to be promoted for its wider benefits to  
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5 drainage, flooding and the urban environment.  
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## 10 **Glasgow**

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16 The City of Glasgow has a population of 580 thousand people and the wider Glasgow and  
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18 Clyde Valley metropolitan region has population of 1.5 million. The Greater Glasgow area  
19  
20 covers 268 square kilometres along the River Clyde, and receives an annual average rainfall  
21  
22 of 1,120mm. Glasgow began building its underground sewer network between 1850 and  
23  
24 1875. Under the direction of the Glasgow Corporation, over 80 kilometres of pipe were laid  
25  
26 to help address pollution and sanitary problems that plagued the city as a result of rapid  
27  
28 industrialisation, population growth and the existing system of open sewers. The system  
29  
30 was built using a series of intercepting sewers (some based on culverting existing  
31  
32 watercourses) that gathered wastewater to be processed at one of three newly constructed  
33  
34 wastewater treatment facilities (Dalmarnock, Dalmuir, and Shieldhall), and then discharged  
35  
36 into the River Clyde. Glasgow's sewers combine surface and wastewater, and as a result of  
37  
38 CSOs the River Clyde and many of its surrounding watercourses have been classified as  
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40 having 'poor' quality waters according the EU Water Framework Directive.  
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### 51 *Stormwater Decision-making*

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56 In response to a major flooding event in 2002 which saw raw sewage deposited in the  
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58 streets and basements of the city, and the imperatives of implementing the EU Water  
59  
60 Framework Directive, Glasgow created the 'Glasgow Strategic Drainage Plan – a

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2  
3 comprehensive assessment of drainage needs across Glasgow and the surrounding towns'  
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6 (Adshead 2002, 1). To create this plan and address the city's legacy position of decaying  
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9 sewers and lack of investment, the city commissioned Hyder Consulting to bring together  
10  
11 'key stakeholders' including Scottish Water, Glasgow City Council, Scottish Environment  
12  
13 Protection Agency (SEPA), Scottish Enterprise Glasgow, and subsequently Scottish Water  
14  
15 Solutions (a consortium of Scottish Water, other water companies and engineering  
16  
17 contractors). The goal of this partnership was not simply to look at gray solutions but to  
18  
19 actively promote and find green possibilities to addressing (or helping to address) any future  
20  
21 flooding.  
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28 The partnership approach that brought together stakeholders and agencies launched with  
29  
30 the development of the Drainage Plan was carried forward with the formation of the  
31  
32 Glasgow Strategic Drainage Partnership, later expanded and renamed Metropolitan  
33  
34 Glasgow Strategic Drainage Partnership (MGSDP). This partnership, led by the Glasgow City  
35  
36 Council, brought together relevant local authorities including SEPA, Scottish Water, Scottish  
37  
38 Enterprise and British Waterways Scotland (which manages Scottish Canals under contract  
39  
40 from the Scottish government). The purpose of the partnership is to find ways to 'upgrade  
41  
42 and modernise Glasgow's drainage and sewerage network to reduce flooding and support  
43  
44 urban development requirements, while improving water quality and the environment'  
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46 (MGSDP 2008, 1).  
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56 The role of SuDS in managing urban surface water was entrenched in this process by the  
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58 Water Environment and Water Services (Scotland) Act (2003) (and its subsequent  
59  
60 amendments), which redefined the term 'sewer' to include SuDS and made Scottish Water

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2  
3 responsible for maintenance and replacement of all shared public SuDS. While all parties  
4 have a role to play in the development and implementation of SuDS, and the Scottish  
5 Government and SEPA encourage all developers to consider the use of SuDS when  
6 retrofitting buildings and properties. One of the shortfalls of the 2003 Act is that it only  
7 requires Scottish Water to adopt approved SuDS systems, which have been integrated into  
8 new developments. Retrofits and non-approved systems remain outside the remit of the  
9 Act.  
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23 Having a requirement for the integration of SuDS in all new developments, Glasgow has  
24 seen a considerable range of SuDS projects completed over the past few years. One of the  
25 largest is designed to reduce the effects of storm flooding in South Glasgow. The  
26 neighbourhoods of East Renfrewshire, Kirkland Bridge, Kittington Bridge were selected for  
27 SuDS redesign integrating 'flood storage areas...(which would) enhance biodiversity through  
28 the creation of artificial wildlife habitats, the creation of woodlands, scrub (lands)... wet  
29 grasslands, shallow scrapes, and ponds' (McGowan & Douglas 2014, 2). The project  
30 attenuates the flow of the White Cart, Earn, and Kittington rivers before their floodwaters  
31 reached Glasgow. Significantly, this project was developed under the guidance of a working  
32 group of SEPA, Scottish Natural Heritage, Scottish Water, local angling groups and fisheries,  
33 RSPB, representatives from three local authorities, and involved active public consultation.  
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53 While green infrastructure is an element of Glasgow's stormwater plan, the core of Scottish  
54 Water's development plan is the construction of several large storage and conveyance  
55 tunnels under the city, the largest of which is a three-mile tunnel to run from Queen's Park  
56 to Craigton industrial estate. Scottish Water describes the £100 million project as:  
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3 The biggest investment in the network since Victorian times, the upgrade will  
4  
5 improve river water quality and the natural environment of the River Clyde and its  
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7 tributaries, enable the Greater Glasgow area to grow and develop, alleviate sewer  
8  
9 flooding and deal with the effects of increased rainfall and climate change. (Scottish  
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11 Water 2013)  
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18 The Scottish Water preference for ponds, basins and large-scale underground storage  
19  
20 tunnels is in part due to existing urban infrastructure, soil type and variation in Glasgow's  
21  
22 average rainfall. Glasgow is built on a complex mix of soils including: wet mud and sand,  
23  
24 boulder clay, solid rock, shale, sandstone, and quicksand. Monthly average rainfall ranges  
25  
26 from highs of 130-140mm in December and January to lows of 60-65mm per month  
27  
28 between April and June. As such, while SuDS are recommended or required in many  
29  
30 documents, the primary techniques tend not to include infiltration and site-specific  
31  
32 practices (as commonly found in the US).  
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41 While there is widespread political and industrial support for the implementation and use of  
42  
43 SuDS in Scotland, a 2013 report by consulting firm Hydro, 'Engineering Nature's Way', found  
44  
45 that of the 151 respondents working in local authorities, SEPA, consulting, homebuilding,  
46  
47 contracting and other sectors, 45% felt that SuDS had only been 'somewhat successful'. This  
48  
49 view was explained to be the result of, 'the constraints put in place by Scottish Water and  
50  
51 the Local Council as to what they are willing to adopt makes it difficult to use the full range  
52  
53 of SuDS features'. More than 84% of respondents believed that more could be done to  
54  
55 advance the retrofitting of SuDS in urban areas. One homebuilder noted: 'Whilst there is  
56  
57 attention being paid to flood prevention in these areas, very little is being done regarding  
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3 SuDS'. The problem associated with retrofitting was a belief (held by over 75% of  
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5 respondents across all sectors) that there was inadequate funding for the adoption and  
6  
7 maintenance of SuDS when considering solutions.  
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## 10 11 12 13 **Washington DC** 14

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18 Washington DC has a population of over 600,000 residents and occupies 158 square  
19  
20 kilometres at the confluence of the Anacostia and Potomac Rivers. DC has an average  
21  
22 rainfall of 1,160mm and sits in the heart of the Chesapeake Bay watershed, which is  
23  
24 currently threatened by hypoxia and eutrophication, despite significant efforts by DC and  
25  
26 other watershed stakeholders to address the situation (Boesch et al. 2001; Chesapeake Bay  
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28 Program, 1987; National Research Council 2008)..  
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36 As the capital city, DC has operated under direct federal control or oversight and the federal  
37  
38 government owns 40% of land, including much of that immediately adjacent to the district's  
39  
40 major water bodies (Chesapeake Bay Program 1996). The District of Columbia Water and  
41  
42 Sewer Authority (DC Water) manages combined sewers and the Blue Plains sewage  
43  
44 treatment plant and its finances are not tied to DC's overall budget (DC Water 2012b; DC  
45  
46 Water ndd). The District of Columbia Department of the Environment (DDOE) is also  
47  
48 integrally involved through management of separate storm sewers and the management  
49  
50 and regulation of DC's waters.  
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58 *Stormwater Decision-making*  
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3 DC's over 60 CSO outfalls (triggered by rain events as little as 2.5mm) continue to be a major  
4 source of impairment for receiving waters (DC Water 2002). In response to legal suits for  
5 Clean Water Act Violations, and under a 2005 consent decree, DC Water created the 'Clean  
6 Rivers Project,' Long Term Control Plan (LTCP) (US District Court for DC 2003). This plan is  
7 designed to reduce CSO overflow volumes in the city by 96% to an estimated 138 mg/avg yr  
8 at an estimated cost of \$2.6 Billion (2001 dollars) (DC Water, 2012b; DC Water, 2014b).  
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21 The plan originally featured the creation of four storage and conveyance tunnels and \$3  
22 million devoted to LID retrofits, largely in the form of demonstration projects (DC Water  
23 2012b). Reasons the initial plan did not include more GI are: lack of information; the high  
24 rate of CSO reductions required; and short timetable for improvements (Ray 2014). The last  
25 two considerations were particularly acute in DC, perhaps because of DC's location in the  
26 sensitive and polluted Chesapeake Bay watershed.  
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39 While grey infrastructure was a component of DC Water's original LTCP, other city agencies  
40 have also encouraged the use of green infrastructure through a variety of policy and  
41 planning instruments, designed to address broader water quality issues. For instance,  
42 DDOE's RiverSmart Homes program provides consultation and subsidies to property owners  
43 for onsite stormwater management (DDOE ndb). In 2010 DDOE and DC Water began to  
44 assess stormwater removal fees tiered to impervious area (DDOE, ndc; DC Water nde). In  
45 2013 DDOE released guidelines requiring all new construction greater than 465 square  
46 metres to retain the first 30mm of rainfall or to combine on-site and off-site retention  
47 through their Stormwater Credit Trading programme (DDOE 2013). In 2013, the DC  
48 Department of Planning instituted the Green Area Ratio, a planning instrument that requires  
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3 all new development and significant renovation projects to incorporate green landscape  
4 elements (DDOE 2014).  
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11 Several converging trends led to the reopening of DC's consent decree in 2014 to include a  
12 significant green infrastructure requirement. First, a significant increase in information  
13 about green infrastructure related stormwater benefits and financial costs have emerged.  
14  
15 In addition, the EPA has clarified and supported the role of green infrastructure in meeting  
16 regulatory requirements (Casey Trees). There were also changes in DC Water. Amongst  
17 these was the 2009 decision to hire George Hawkins as CEO and General Manager, a man  
18 with a background as an environmental advocate, director of the DDOE, and chair of the  
19 committee to develop DC's sustainability plan  
20  
21 (<http://www.dewater.com/about/hawkins.cfm>). Finally, around this time, the financial  
22 implications of the current consent decree became increasingly clear. Of particular concern  
23 was the effect of rising sewerage rates on low-income residents (DC Water 2014b; Ray  
24 2014).  
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43 In 2016, the *Long Term Control Plan Modification for Green Infrastructure* was officially  
44 accepted. This plan fully replaces one of four newly planned CSO interceptor tunnels with a  
45 green infrastructure investment of \$90 million, addresses overflows to the Potomac through  
46 a combination of grey-green infrastructure, and gives the city an additional five years to  
47 complete the project (DC Water 2014b). DC Water justifies this change citing added social,  
48 environmental and economic benefits, reduced financial impact on ratepayers, and synergy  
49 with the Mayor's Sustainable DC Plan (DC Water 2014b; DDOE nd). While community and  
50 advocacy groups generally support the inclusion of green infrastructure, concerns about the  
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3 plan have also been articulated. These include: 1) the effects/necessity of delays in the  
4 timetable relative to the initial LTCP; 2) accountability being tied to budget spent on green  
5 infrastructure rather than environmental outcomes; 3) insufficiently articulated  
6 maintenance and repair costs and protocols, and 4) the unfortunate clustering of green  
7 infrastructure projects within the city—significantly *not* occurring in some of the poorest  
8 communities neighbouring the Anacostia River (NRDC, nd; Chavez, 2014; Fellows, 2014).  
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## 21 Philadelphia

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25 Philadelphia is the sixth largest US city, with a population of over 1.5 million (down from a  
26 peak of 2 Million in the 1950s) within its 347 square kilometres. Philadelphia is particularly  
27 diverse, with over 44% of its population identifying as African American, but faces  
28 challenges with 26% of residents living below the poverty level (US Census Bureau 2012).  
29  
30 Despite high levels of poverty, in many ways Philadelphia has been a pioneer in water  
31 management. It was the first US city to take on water supply as a municipal responsibility in  
32 1801 and later created the 45-hectare Fairmount Park in the middle of the city to protect  
33 the city's water supply (City of Philadelphia nd). The Philadelphia Water Department (PWD)  
34 was created in the 1950s as a municipally owned and financed department, to manage  
35 drinking water and wastewater services. Currently, the PWD maintains three wastewater  
36 treatment plants and nearly 4,828 km of sewers (60% of which are combined) within the  
37 city and neighbouring 596 square km of suburbs (Holst 2007). Philadelphia receives about  
38 1,043 mm of precipitation per year and has well-drained soils, yet—due to development on  
39 historic tidal marsh—experiences flooding and subsidence in some areas (PWD 2009).  
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Several developments paved the way for Philadelphia’s current 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 within its system 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).

### *Stormwater Decision-making*

In order to comply with the federal Clean Water Act, PWD first examined the costs and benefits of various CSO management options utilising 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 primarily due to non-water-related benefits including reductions in heat-stress mortality,

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3 improved aesthetics and property value, and increased recreational opportunities  
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6 (Maimone et al. 2011).  
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11 Based on these findings, in 2009, the PWD created a green infrastructure-based Long Term  
12  
13 Control Plan which, as 'the single largest investment in the City's environment over the next  
14  
15 25 years...presents a unique opportunity to be much more than just a water quality  
16  
17 improvement program.' Philadelphia's 'Green City, Clean Waters' plan sets out an agenda  
18  
19 spending \$2.4 billion between 2011-2026, 67% of which will be spent on green  
20  
21 infrastructure techniques (DeGood 2013). As such, it is a commitment to reshape the city  
22  
23 (US Housing and Urban Development 2013) by developing 'the most extensive urban  
24  
25 network of green infrastructure in the United States', and using Philadelphia's vacant land  
26  
27 as a resource (Natural Resources Defense Council nd).  
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36 This plan has since been formalised through a Consent Decree and Partnership Agreements  
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38 with the EPA and state authorities (EPA 2015). The objective is to create 9,500 'Greened  
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40 Acres' over 25 years. That is, to convert nearly 40.5 km<sup>2</sup> of impermeable surfaces to manage  
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42 25mm of runoff onsite and reduce overflows by 85% through projects on both public and  
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44 private property (Maimone et al. 2011; Water Environment Federation 2014). The city owns  
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46 approximately 45% of impervious surfaces within the CSO area and will integrate green  
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48 infrastructure into capital improvement projects on city-owned streets, sidewalks, and  
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50 properties. Other public land projects include a large-scale street tree planting programme;  
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52 preserved open space—including dedication of vacant and abandoned lands, and stream  
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54 restoration (City of Philadelphia 2011; US Housing and Urban Development 2013).  
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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<sup>2</sup> of newly pervious area (City of Philadelphia 2014).

## Discussion

Comparing different responses to CSOs in four cities reveals key factors influencing urban environmental decision-making, summarised in Table 1.

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

	London	Glasgow	Washington DC	Philadelphia
<b>Environment</b>	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.
<b>Regulation</b>	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.

<b>Governance</b>	Private ownership of infrastructure. EU Directives. Local government jurisdiction uncertain.	Public ownership of infrastructure via Scottish Water. EU Directives. Range of Scottish Acts and building regulations.	DC water is independent authority of DC. DDOE manages MS4s and responsible for receiving water quality. Federal ownership of 40% of land area.	PWD is municipally owned and financed.
<b>Economics</b>	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.
<b>Society</b>	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.
<b>Leadership</b>	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.

Local environmental conditions such as rainfall, receiving water quality, soil type, climate change forecasts and urban density influence the technical feasibility of different options. For instance, London's clay soils and high density urban form reduce opportunities for infiltration and local storage of stormwater, while Philadelphia's well drained soils and areas of abandoned land made green infrastructure solutions more feasible. Further, Washington DC's location in a sensitive and tightly-regulated watershed—the Chesapeake Bay—has resulted in that city facing much higher requirements for CSO overflow volumes reduction than other US cities. This means that DC must control larger storm events than Philadelphia, for example, and large storm events are harder to control with green infrastructure than small and medium sized events.

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6 The governance of urban drainage infrastructure, including ownership, planning and  
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8 regulation, influences decision making about responses to CSOs. London was unique of the  
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10 four case study cities in that its drainage, sewerage and wastewater infrastructure are  
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12 privately owned. The decision-making process in London involved a range of stakeholders  
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14 and was highly scrutinised by government agencies and independent regulators. However,  
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16 the separation between privately owned infrastructure and public responsibility for urban  
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18 planning in London is less conducive to institutional integration and flexibility, which was  
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20 evident in cities that placed greater emphasis on green infrastructure solutions. Municipally  
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22 focused responses to CSOs in the two US based case studies enabled the implementation of  
23  
24 a wider range of planning and regulatory instruments to promote green infrastructure than  
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26 in the UK cases, especially London. Philadelphia, the only city in our sample to focus entirely  
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28 on green infrastructure, chose this option primarily based on assessments of the non-water  
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30 benefits to their community. Crucially, its public water department was able to define its  
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32 mission broadly, breaking with traditions of more narrowly defined service provision.  
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43 The economic context of each city and the ownership of its infrastructure influenced the  
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45 viability of different options for reducing CSOs. Private ownership, secure income through  
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47 regulated water charging, and central government underwriting as a project of national  
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49 importance, provide a structure for capital investment for the interceptor tunnel in London.  
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51 By contrast, municipal governments in DC and Philadelphia are highly constrained in their  
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53 ability to raise capital and increase sewer charges, providing a driver for less capital-  
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55 intensive green infrastructure solutions.  
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4 Social drivers in decision-making about drainage are evident in the integration of green  
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6 infrastructure into urban regeneration planning for post-industrial Glasgow and  
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8 Philadelphia. Environmental justice concerns about the impact of CSOs on poor  
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10 neighbourhoods compared to the benefits of green infrastructure in wealthier  
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12 neighbourhoods have shaped debate in Washington DC. Social engagement in London has  
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14 mostly been limited to protests by residents and local politicians in boroughs most impacted  
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16 by the construction of the tunnel, and support by recreational users of the river.  
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24 The role of strong local leaders in making the case for green infrastructure solutions was  
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26 evident in Philadelphia, Washington DC, and Glasgow but notably absent in London. In  
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28 London the main proponents of SuDS solutions were outside Thames Water and key  
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30 regulators and decision makers, and were therefore positioned as opponents to the tunnel.  
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32 In Glasgow and the US cities, strong individual leaders within the water utilities and city  
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34 government were able to demonstrate the wider values of green infrastructure and achieve  
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36 change across institutions by linking to broader environmental and sustainability objectives  
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38 despite some uncertainty about green infrastructure implementation at scale and related  
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40 costs, including maintenance.  
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## 49 **Conclusion**

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54 Combined sewers represented a standard engineering response to nineteenth century  
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56 public health crises, but responses to the problem of CSOs in the twenty-first century are  
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58 more divergent. Local environmental, economic, political and social conditions are shaping  
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3 technical decisions about how to solve CSOs. Comparing London, Glasgow, Washington DC  
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5 and Philadelphia shows that the choice of 'green' or 'grey' solutions is highly dependent on  
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7 diverse factors such as access to capital investment, institutional flexibility, local leadership  
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9 and urban social context. Technical constraints also contribute to grey and green  
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11 infrastructure choice.  
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20 As post-industrial cities follow different economic, social and political pathways, their  
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22 infrastructural choices are also diverging. Green infrastructure solutions are more viable in  
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24 Glasgow, Washington DC and Philadelphia where drainage infrastructure is still publically  
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26 owned and a wider range of policy instruments are used to promote sustainable and  
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28 decentralised solutions. An interceptor tunnel was more viable in London where the  
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30 economic and regulatory structure of the industry supported large capital investment. While  
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32 proponents of green infrastructure frame these solutions within narratives of progress  
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34 towards urban sustainability, the complexity of urban development and infrastructure  
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36 governance means that this may not be the next paradigmatic, universal response to urban  
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38 drainage challenges.  
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