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The potential to retrofit SuDS to address combined sewer overflow discharges in the Thames Tideway catchment

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Abstract

Experience of retrofitting SuDS in the UK is limited, and there are no well-established procedures for evaluating the feasibility, value, or cost-effectiveness of doing this, particularly at the catchment scale. This paper demonstrates a two-phase process for evaluating the potential to retrofit SuDS to address combined sewer discharges in three subcatchments within the Thames Tideway catchment of London. The first phase evaluates what might be achieved with various levels of disconnection ('global' disconnection scenarios) using hydraulic models, whilst the second phase considers how disconnection might practically be achieved. High levels of disconnection are technically possible, but practicably difficult. In selected cases, and with aggressive implementation of SuDS, CSO discharges could potentially be eliminated or reduced to acceptable levels without the need for any modifications to underground assets. However, retrofit SuDS could not eliminate the requirement for some form of sewer modification in any subcatchments.

Keywords

Combined Sewer Overflows (CSO); Geographic Information Systems (GIS); Retrofit SuDS; Stormwater management.

Introduction

Retrofit SuDS

Many urban areas experience problems with excessive Combined Sewer Overflow (CSO) discharges and/or basement and street flooding, with consequent aesthetic, water quality and property damage impacts. In many cases these problems have been induced or exacerbated by the progressive urbanisation of the local catchment, and may worsen further as a result of climate change, population growth and land use change. Improving problematic CSO discharges and addressing property sewer flooding are key elements of the Asset Management Programmes (AMP) in England and Wales and the Quality and Standards programmes in Scotland. The EU's Water Framework Directive (WFD, 2000/60/EC) provides supporting legislation aimed at delivering water quality improvements, although the earlier Urban Waste-Water Treatment Directive (UWWTD, 91/271/EEC) specifies the compliance requirements. Combined sewer overflows are a significant cause of poor water quality in urban water courses.

CSO and surface water flooding problems are typically resolved using engineered solutions that are implemented within the sewer network. For example, in-sewer storage (e.g. a storage chamber or oversized sewer pipes) is widely used to resolve catchment problems by storing excess flows, and releasing them back into the sewer once peak storm flows have subsided. The design, construction, operation and maintenance issues associated with in-sewer storage are well understood; and these approaches are widely implemented within the UK (FWR, 1998) and elsewhere. However, this approach is not necessarily optimal. Such schemes miss opportunities to utilise water as a resource, and cannot deliver amenity or water quality benefits beyond those associated with volumetric attenuation. In-sewer storage may lead to increased energy requirements if the stored stormwater needs to be pumped and/or passes through a treatment works further downstream. This contravenes the emerging regulatory requirements on water companies to reduce their carbon footprint.

The Environment Agency for England and Wales (EA) and the Scottish Environment Protection Agency (SEPA) actively promote the use of Sustainable Drainage Systems (SuDS) (CIRIA, 2007) for the management of surface water runoff. SuDS include, amongst others, green roofs, rain gardens, soakaways, swales, permeable pavements, infiltration basins and ponds. Because of their reliance on natural catchment processes (i.e. infiltration, attenuation, conveyance, storage and biological treatment) these techniques are seen to constitute a 'more sustainable' approach to stormwater management. Internationally SuDS-type approaches are incorporated within Best Management Practices (BMPs), Low Impact Development (LID), Water Sensitive Urban Design (WSUD) and, most recently, Green Infrastructure (e.g., Melbourne water, 2005; Wong, 2006; USEPA, 2007; USEPA, 2010; and Ashley *et al.*, 2011).

Although SuDS usage is being actively promoted for new developments in the UK, the potential to make use of SuDS within *existing* urbanised areas has received only limited attention. The term **retrofit** is employed when SuDS-type approaches are intended to replace and/or augment an existing (combined or separate) drainage system in a developed catchment. An example of retrofit SuDS would be the disconnection of roof runoff from a combined sewer and its diversion on to a lawn, into a garden pond or soakaway, as is now compulsory in Toronto, Canada (Toronto, 2010). Retrofit SuDS approaches seek to remove the storm-water component from the piped drainage system, thereby increasing the effective capacity of the sewer system, eliminating treatment/pumping costs and energy requirements. They may also make positive contributions to urban water quality, habitat, amenity and other benefits associated with green infrastructure. Desk-based feasibility studies relating to the potential usage of retrofit SuDS have suggested that retrofit SuDS could provide cost-effective components of catchment rehabilitation strategies (Stovin and Swan, 2007; Smullen *et al.,* 2008; Stratus Consulting, 2009; USEPA, 2010). Preliminary decision-support tools aimed at identifying opportunities and approaches to SuDS retrofitting have also been proposed (e.g. Weinstein *et al.,* 2006; Stovin and Swan, 2007; Digman *et al.*, 2012).

There are several international examples of this type of approach being successfully implemented, including the Portland (Oregon, USA) downspout disconnection programme as part of their Cornerstone CSO Control Project (Portland Online, 2006) and the extensive SuDS retrofit undertaken in Augustenborg, Malmö (Sweden) (Stahre, 2008). Some smaller UK examples include work undertaken to retrofit SuDS into schools (CIRIA, 2011) and a large retrofit green roof implemented by Lambeth Council (2011).

Smullen *et al.* (2008) and Stratus Consulting (2009) highlight the opportunities provided by urban regeneration to engineer a gradual transformation from conventional piped drainage to SuDS within the existing urban cores as part of the City of Philadelphia's long term CSO Control Plan. They describe "*an innovative planning approach .. [that] promotes control of stormwater at the source through low impact development and low impact redevelopment retrofit, supported by new stormwater regulations and other progressive practices such as street tree planting and riparian buffer creation and restoration.*" The programme in Philadelphia is named "*Green City, Clean Waters",* and the case study suggests that such an approach may be used to provide long term improvements in stormwater management, together with a range of other multi-value benefits consistent with an ecosystem services approach. The USEPA's Storm Water Management Model (SWMM) was used to evaluate the operational characteristics and benefits of low impact development and redevelopment management practices. Simulation results for one sewer network sub-catchment in Philadelphia suggest that the total annual volume of CSO discharges could be halved (from 2000 to 1000 million US gallons) by increasing the percentage of land area served by land-based controls from 0% to 50%. Using Green Infrastructure and disconnecting 50% of the City's stormwater incrementally over time has also been shown to bring almost $2.2bn of added-value benefits to Philadelphia, including reductions in carbon emissions and heat island problems (Philadelphia Water Department, 2009). The city of Philadelphia has a population of 1.5 million and a population density of approximately 4,400/km^2 (United States Census Bureau, 2010) which is in contrast to the population of 5.6 million contributing to the Thames Tideway catchment which has a population density of 10,100/km^2 (Needs Report, Thames Water, 2010).

These studies have also shown that this level of disconnection might reasonably be achieved through a combination of measures, including stormwater management planning regulations, financial incentives, specific projects aimed at retrofitting/greening public spaces and streets, as well as measures introduced as part of a major new waterfront redevelopment initiative. Initiatives are underway to encourage private enterprise to engage in these disconnection initiatives, and studies have shown this to be cost-effective and attractive to developers and others (Ritchie, 2010).

However, recent work aimed at designing and implementing retrofit SuDS at a larger, catchment scale (Stovin *et al*., 2007) has suggested that retrofit SuDS are difficult to implement within the current UK regulatory environment. Present legislation appears to promote the use of 'quick fix' solutions to sewer problems; and incentives for any of the key stakeholders (e.g. water utilities or local authorities) to adopt and maintain SuDS are in embryonic stage of development. It needs to be recognised that the diverse range of benefits would actually accrue to a multitude of stakeholders, and it remains unclear how SuDS should be funded. In this context, the construction of retrofit SuDS will frequently appear to be disruptive, risky, expensive and not cost-beneficial when compared with traditional 'grey' solutions. The English and Welsh water companies are required to maintain a register of local properties considered to be at risk of internal sewer flooding on average once every five years. The information is provided to the regulatory body – OFWAT – and is used as one of the factors driving their capital programme. The register is known as the DG5 register. To date there are no medium or large-scale examples of a local authority or UK water company retrofitting SuDS to address a drainage, CSO or DG5 (property sewer flooding) problem. Even with the advent of the Flood and Water Management Act 2010 in England and Wales, this is unlikely to change, as the Act only applies to new construction and redevelopment and has no direct authority to require retrofitting. However it should be noted that the Water White Paper released in December 2011 made explicit reference to retrofitting SuDS and the role of champions and behaviour change in delivery.

This paper will present a case study evaluation of the potential to implement retrofit SuDS to address a large-scale CSO problem as part of the London Tideway Improvements. The paper will focus on the identification of potential SuDS options and their hydraulic performance evaluation, implementation costs and practical considerations.

The London Tideway Improvements and the proposed Thames Tunnel

The following paragraphs provide a brief overview of Thames Water's proposals for the London Tideway Improvements, which include the Thames Tunnel (Thomas and Crawford, 2011; Thames Water, 2012). The improvements are required to meet the UWWTD and WFD. London's Victorian sewerage system was designed to overflow into the River Thames during wet weather when the combined sewers reached capacity, to prevent homes and streets from flooding. However, the system is now struggling to cope, and discharges happen much more frequently than was originally envisaged, currently over 50 times in a typical year, with a total annual discharge of about 39 million m^3.

Based on cooperative studies with regulatory agencies, Thames Water has developed three major engineering schemes to control sewer overflows and improve water quality in the tidal River Thames: upgrades to five sewage treatment works in London; the construction of the Lee Tunnel and the proposed Thames Tunnel. The improvements to the treatment works will expand capacity and treatment and are expected to be completed by 2014. The Lee Tunnel is a 6km long 7.2 m diameter tunnel that in combination with the upgrade in treatment capacity at Beckton STW, controls overflows from the largest CSO in the system. The Lee Tunnel is expected to be completed in 2014.

The Thames Tunnel

The Thames Tunnel is designed to be a 7.2 m diameter sewer up to 32 km in length, which will run from west to east London, up to 75 metres below ground, broadly following the route of the River Thames. It will control flows originating from the 34 most polluting sewer overflows, as identified by the Environment Agency, before transferring flows to Beckton sewage treatment works for treatment. Thames Water have now rationalised the tunnel route to a shorter (25 km) route that takes advantage of the Lee Tunnel. It will broadly follow the river from its starting point in west London to the east of Tower Bridge at Limehouse before going northeast to connect to the Lee Tunnel at Abbey Mills in Stratford.

In autumn 2008 Thames Water began a two phase process of consulting the London local authorities and stakeholders who could potentially be affected by the construction of the Thames Tunnel. Other pan-London stakeholders involved in this process are the Environment Agency, the Port of London Authority and the Greater London Authority. Phase One public consultation was held in the autumn of 2010, with Phase Two due to start in November 2011. To give an idea of the scale of the investment required to deliver the required improvements, the anticipated cost (2011) of building the Abbey Mills route of the Thames Tunnel is £4.1bn.

In addition to developing the Thames Tunnel proposals, Thames Water undertook a parallel investigation to evaluate the extent to which retrofit SuDS might fully or partially address the CSO problem. The evaluation was based upon hydraulic performance and whole-life costs and did not attempt to quantify the full range of costs and benefits as would be expected in a Green Infrastructure or Ecosystem Services approach. This paper provides a summary of that work. The data reproduced here was originally presented as 'Appendix E – Potential Source Control and SuDS Applications' (Ashley *et al.*, 2009) within the technical documents associated with the Needs Report (Thames Water, 2010) and first phase consultation.

Methodology – Generating and evaluating options

Annex 1 of Appendix E of the Needs Report summarises the catchment hydraulic modelling work undertaken by the London Tideway Tunnels Delivery Team to evaluate the potential for control of CSO discharges associated with various retrofit SuDS strategies. The strategies investigated were identified by the authors and are discussed in the following sections.

Subcatchment selection

Based on an assessment of CSO characteristics, sewer system connectivity and land-uses within the entire London Tideway Tunnels (LTT) catchment, three subcatchments were identified as being likely to have the greatest potential for controlling CSO discharges through SuDS retrofitting. The three example areas are located in the southwest of the catchment, south of the River Thames. These three areas represent the subcatchments contributing to the West Putney, Putney Bridge and Frogmore (Buckhold Road) CSOs (Figure 1). West Putney comprises 425 ha mixed-use urban area; Putney Bridge and Frogmore (Buckhold Road) are 142 ha and 454 ha respectively. The three areas are broken into 7, 4 and 9 subcatchments respectively in the hydraulic model. Table 1 provides an overview of the predominant land-use characteristics in each subcatchment.

Table 1 Land-use descriptions

	Land-use description	Example images
West Putney	Northern and South-western parts of the catchment are dominated by golf courses. The centre of the catchment is dominated by large, medium rise apartment blocks often set in large communal grounds	 Medium rise apartment blocks in communal grounds
Putney Bridge	Characterised by high-density development, narrow roads, residential areas with small/no front gardens or off-road parking	 Typical high density housing
Frogmore (Buckhold Road)	There are many large apartment blocks within this catchment. To the North-east of the subcatchment, the dominant housing type is medium density residential, often with wider roads than other residential areas, and large front and back gardens. Many houses have off-street parking. The southern area of this subcatchment is dominated by a mix of high-density terraced/semi detached housing and apartment blocks. At the centre of the catchment there is a large area of maintained woodland and grass (Putney Heath) There are also many institutional buildings (Schools, hospitals, university campus), often set in large grounds.	 Medium density residential  Institutional buildings set in grounds  Putney Heath

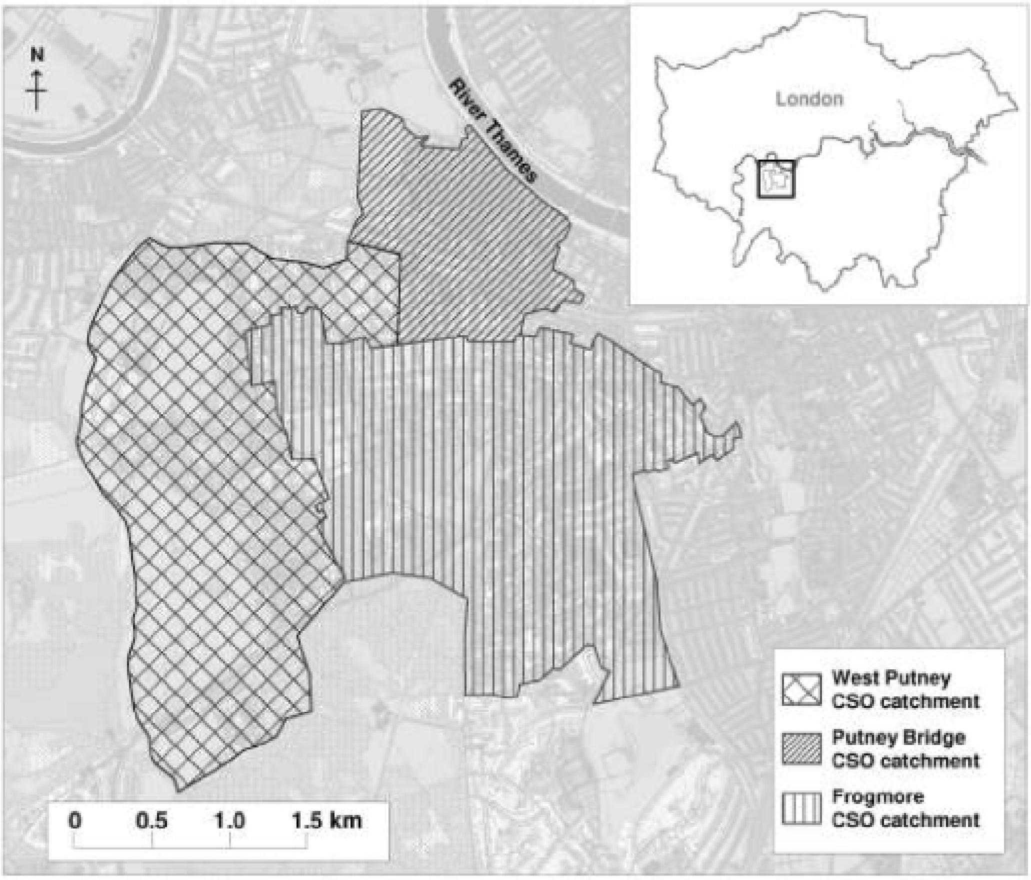

Figure 1 Location of the three subcatchments investigated. © Crown Copyright / Digimap 2011. An Ordnance Survey/EDINA supplied service.

Retrofit SuDS option generation and hydraulic evaluation

The retrofit SuDS option generation broadly fell into two phases, with the initial phase considering 'global' disconnection scenarios and the second phase focusing on maximum practicable disconnection scenarios, in which preference hierarchies were developed to identify technically-feasible and practical disconnection options given basic land-use characteristics. The concept of employing two levels of assessment – global disconnection and outline scheme design – is also advocated in the recently-published CIRIA guidance on retrofitting surface water management measures (C713, Digman *et al.,* 2011). In each phase, catchment hydrologic and hydraulic modelling tools were employed to estimate the number, volumes and flowrates associated with CSO spills. A final phase of 'refined' option development was undertaken, although no hydraulic modelling was undertaken as the refined disconnected area resulted in less than the 50% impermeable area global disconnection scenario that had been modelled and evaluated.

The London Tideway Tunnels catchment is being modelled using the InfoWorks CS simulation package, which represents the sewerage system via over 5,000 pipes and 1,110 subcatchments. Because of the complexity of the sewer network it was not possible to model every individual sewer (approximately 100,000) and pruning of the overall sewer network was necessary. SuDS units, especially those used for source control, operate at a very local scale and caution is required when using large-scale sewerage models to represent SuDS. No attempt has been made to model specific SuDS units, rather their effects in terms of changing the representation of the subcatchment drainage area components, the stormwater runoff and inputs to the sewer network have been modelled. The catchment model was amended to reflect the SuDS implementation scenarios developed. The primary changes to the catchment model were adjusting percentages in the various area types (pervious, impervious and connected area) contributing to the model nodes and/or via the adjustment of initial loss parameters.

Rainfall event selection

System performance was evaluated against the December typical year and October 2000 events, which relate to a one in two year return period and a one in four year return period respectively and represent the most severe events (in terms of CSO volume) of the typical year and the Compliance Test procedure (CTP) rainfall event series (April to October events). The complete typical year rainfall (October 1979 to September 1980) was also simulated for selected scenarios to provide a representation of the number of spills and total overflow volume that could be expected annually at the CSOs with implementation of the SuDS scenarios. The typical year series contains the December event and over 50 other rainfall events that are typical to the LTT catchment. The local rainfall depths for the three main simulation events were as follows: December typical year, 44 mm; October 2000, 43 mm; and the typical year, 565 mm. Peak 5-minute rainfall intensities in the two primary simulation events and the entire typical year were 10, 24 and 68 mm/hr respectively.

Global disconnection scenarios

'Global' disconnection scenarios were applied to the West Putney, Putney Bridge and Frogmore (Buckhold Road) CSOs. The purpose of this preliminary modelling exercise was to assess the extent to which the disconnection of surface water inputs could impact on CSO discharges, and to get some idea of the level of disconnection required. Clearly there would be no justification for undertaking detailed design of retrofit SuDS schemes if it was evident that even high levels of disconnection would have no, or limited, impact on overall system performance. Given the highly-interconnected nature of the sewer network, and the fact that the system has limited capacity, even in dry weather, it would not be appropriate to assume that widespread disconnection would achieve as much as might be hoped for.

The global disconnection scenarios considered were: 25% impermeable area transferred to permeable area; 25% impermeable area removed; 50% impermeable area transferred to permeable area; 50% impermeable area removed; and 5 mm of rainfall lost at the beginning of the storm. In the scenarios where impermeable area is transferred to permeable area it should be noted that the permeable area is still connected to the sewer network and could – depending primarily on rainfall intensity – result in runoff and inflow to the sewers. The 5 mm initial losses scenario was intended to represent the widespread implementation (i.e. to > 50% of all roofs) of source control devices such as green or blue roofs. Blue roofs are non vegetated roofs, designed to create temporary ponding and thus provide some level of stormwater retention and detention.

Maximum practical disconnection scenario

The global disconnection studies provide an initial indication of the potential effectiveness of different scales of disconnection. The second phase of the assessment concerns the identification of specific SuDS measures that might practically be utilised and implemented within the sample subcatchments and an assessment of the required levels of disconnection. In this case a preliminary investigation was undertaken to identify the maximum possible levels of disconnection that might be achieved, based on physical (i.e. land-use) constraints alone.

No well-established methodologies exist for deciding which – from the wide array of SuDS options available – will provide an optimal solution for a specific catchment or CSO control target. This is partly because the judgement of optimality is a multi-objective problem in which priorities may change in time and from one location to the next. Flow quantity control must be balanced with the aspiration to also provide water quality improvements and to provide scope for enhanced public amenity & biodiversity, all of which are constrained by costs, operation and maintenance and other practical implementation issues. In this instance a pragmatic view was adopted, and preference was given to those SuDS options expected to deliver the greatest hydraulic performance benefits. However, it was presumed that the use of SuDS would deliver greater water quality and amenity benefits compared with a more-conventional underground-storage-based option.

Stovin and Swan (2007) generated an hierarchical framework for prioritising retrofit SuDS stormwater disconnection options for the reduction of CSO spill frequency. The framework embodies three hierarchies, constructed around urban surface type, the surface water management train concept, and the mode of operation of the device. The hierarchies direct the user to consider publicly-owned surfaces before privately owned surfaces, large roofs before smaller (residential) roofs, source controls before off-site controls and retention/infiltration systems in preference to storage-based systems.

Building on the Stovin and Swan (2007) hierarchical approach, an hydraulic preference hierarchy was established with SuDS options that would completely remove stormwater preferred to those that would direct stormwater to permeable surfaces or options that provide only finite initial losses (e.g. a green roof); least preferred were those that provided only detention storage without significant retention/removal.

The scale of the case study application precludes the use of manual scheme identification approaches; a more strategic and automated approach is required. Geographic information system (GIS)-based decision-support tools have been developed to allow the combination of urban stormwater models with decision-support systems to provide a more user-friendly representation of the modelling outputs (e.g. Viavattene *et al.,* 2008 & 2010). Many of these decision support systems provide assessment criteria to assist in the selection and evaluation of SuDS options based on site characteristics, effectiveness, cost or other socio-environmental factors such as amenity. The key benefits of these tools are that large volumes of data can be collated in a user-friendly manner. However, the approach is still relatively data intensive; the tool developed here is intended for a more strategic level of assessment.

The SuDS option selection and mapping was automated using the GIS package ArcView (v9.3). OS MasterMap data (1:1250) includes several generic land-use types. These are: 'Roads Tracks and Paths (RTP)' (which includes roads, pavements and paths/tracks); 'Buildings'; 'Land' (which can be further subdivided into 'manmade', 'natural' and 'mixed') and 'Other'. A series of logic-based Structured Query Language (SQL) rules was established that enabled parcels of land deemed suitable for specific SuDS retrofit options to be identified, based on their physical characteristics and/or spatial location (see Moore *et al*. (2011) for further details).

The spatial selection of land parcels generates multiple layers indicating locations where each specific retrofit SuDS measure may be feasible. In cases where more than one option may be feasible in any given location, preference was given to the options judged likely to be hydraulically most effective, see Table 2. Checks were also undertaken to ensure that the same permeable surfaces were not utilised for diversion from multiple disconnected impermeable areas.

The 'practical' disconnection scenarios were intended to provide a realistic representation of the level of disconnection that might technically be feasible, though without reference to costs and/or public acceptability issues. These scenarios included the introduction of 25 mm initial losses and storage/attenuation hydraulic modelling options, in addition to the previously-considered removal or transfer to permeable. The 25 mm initial losses scenario was intended to represent SuDS options capable of offering significant levels of retention, but which would ultimately discharge into the sewer once the retention capacity was exceeded. This would include, for example, storage swales, oversize water barrels and permeable pavements.

The reassignment of contributing area type for catchment modelling is shown in Figure 2. This option, subsequently referred to as the 'Maximum practical disconnection option', provided approximately 75% reduction in directly-connected impermeable area overall.

It should be appreciated that the SQL-based SuDS option feasibility assessment tool, the hydraulic performance hierarchy and the approach used to model these potential SuDS retrofit scenarios are all tools/approaches under development. It is hoped that similar studies in the future will enable the methods to be refined and provide greater insights and confidence in their application. One significant limitation of the current implementation of the SQL-based assessment tool is that no attempt is made to identify potential SuDS treatment trains, and that the SuDS approaches considered are predominantly local source controls; that is, regional scale controls are excluded from consideration.

Table 2 Land-use types, retrofit SuDS options, and assumptions used in catchment modelling

Impermeable land-use	SuDS retrofit options (in preference order)	Impermeable area removed	Impermeable area transferred to permeable	Initial losses (25 mm)	Storage/Attenuation
Building Roofs	Disconnect to garden soakaways	✓			
	Disconnect to lawns		✓		
	Oversized Water butts†			✓	
	Green/blue roofs		✓	✓	
Non-road hard standing	Permeable surface			✓	✓
	Disconnect to adjacent permeable		✓		
	Offsite – local detention				✓
Other manmade surfaces	Disconnect to adjacent permeable		✓		
Roads	Permeable surface			✓	✓
	Disconnect to adjacent permeable/SEA streets		✓		
	Pocket street infiltration			✓*	
	Offsite – detention with swale conveyance				✓

*Initial losses of 12 mm

†Water butts assumed to be applied to the rear half of properties only, and to be designed to offer controlled discharge back to the sewer once capacity allows, i.e. assumed empty for subsequent rainfall events. A 0.875 m^3 butt would retain 25 mm rainfall from 50% of a typical 70 m^2 roof.

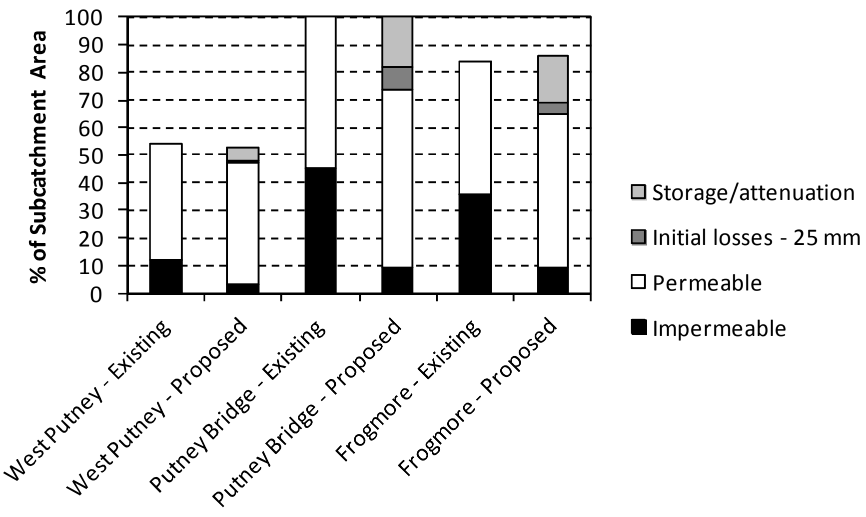

Figure 2 Change in surface characterisation used in the catchment model corresponding to the Existing and Maximum practical disconnection scenarios

Results

Quantitative results for the typical year storm events and the significant October 2000 event are presented in Table 3, and selected comparisons are presented graphically in Figures 3, 4 and 5. Figure 3 compares the percentage reduction in CSO spill volume associated with various retrofit SuDS global and practical disconnection scenarios, compared with the existing case CSO volume. Figure 4 compares the maximum flow rates and Figure 5 considers spill frequency.

Global disconnection scenarios

As would be expected 50% transfer/removal has greater impact than 25% transfer/removal, with the removal of impermeable area having marginally greater impact than transfer to permeable in all cases. The Putney Bridge and Frogmore subcatchments show particularly promising results for the potential disconnection, but – as noted above – these subcatchments were selected because of their promising land use and CSO characteristics. For the typical year, the 50% removal option results in reducing all three CSO parameters; number of events, maximum flow rates and total overflow volume. For Frogmore (which shows the best response to SuDS retrofiiting), for example, the number of events is reduced from 29 to 10 (-66%), and the total overflow volume from 94,500 m^3 down to 21,400 m^3 (-77%). The number of events producing over 1000 m^3 is also significantly reduced at all three CSOs. The target number of overflows in the typical year is 4 per year (Needs Report, Thames Water, 2010). The impact of removing the first 5 mm of rainfall (via storage in blue/green roofs etc) has little impact on the large storms considered here. However, a greater depth of 50 mm would have been sufficient to contain each of the rainfall events in the typical year but widespread capture of 50 mm of rainfall would be practically impossible to achieve.

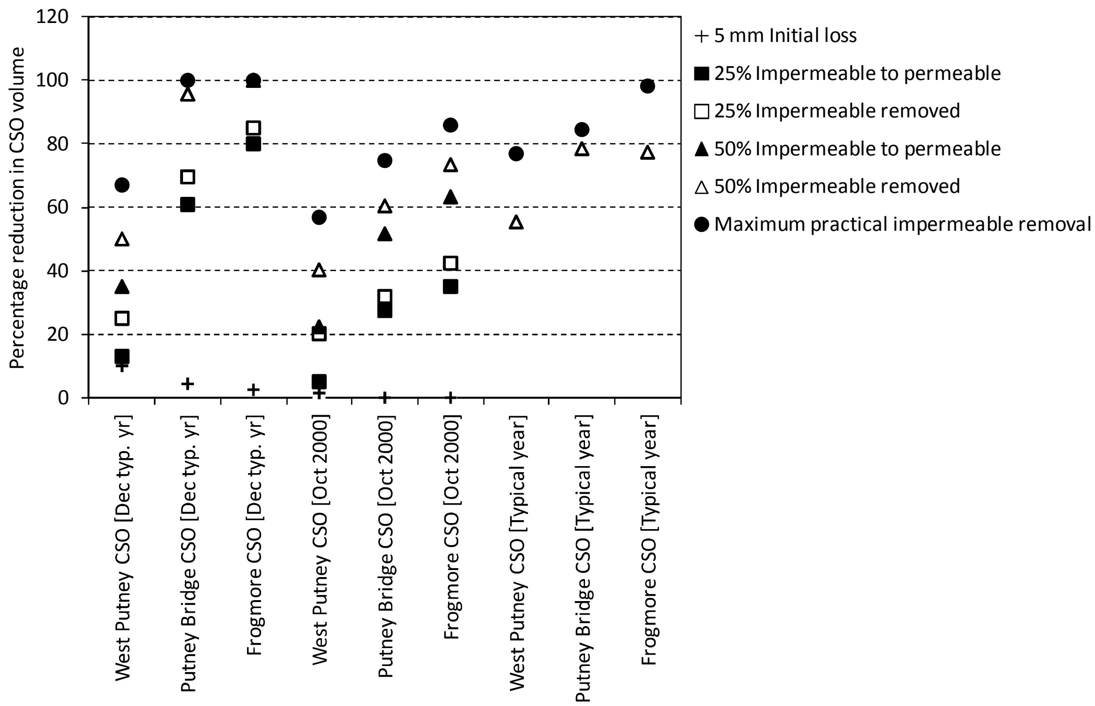

Figure 3 CSO Volume reductions for a range of different disconnection scenarios and storm events

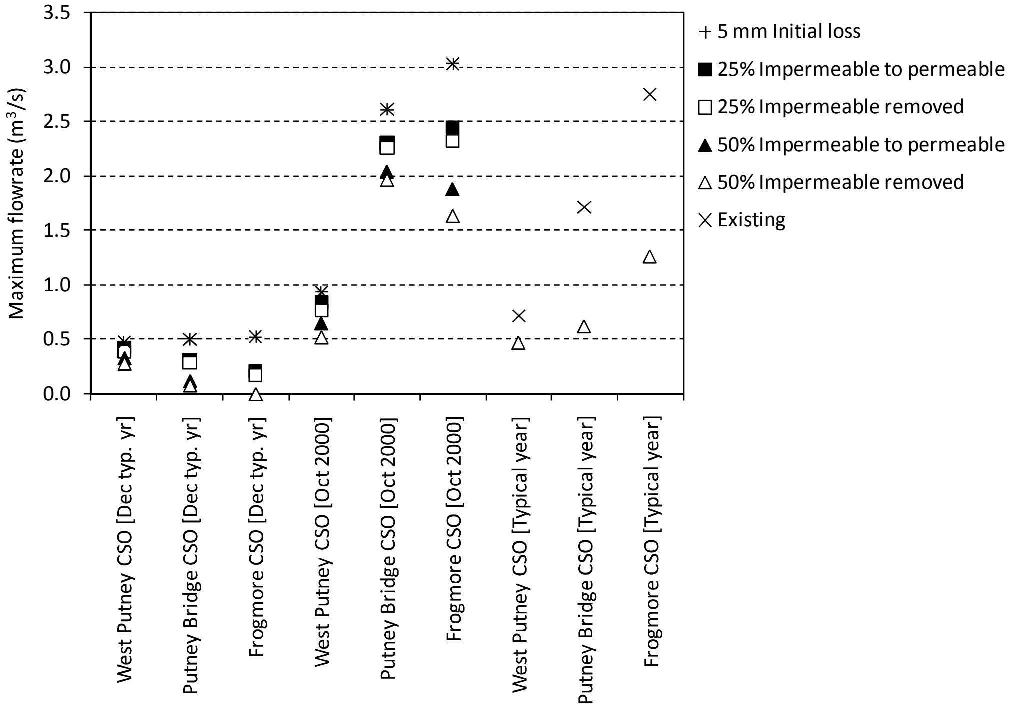

Figure 4 Maximum CSO flowrates for a range of different disconnection scenarios

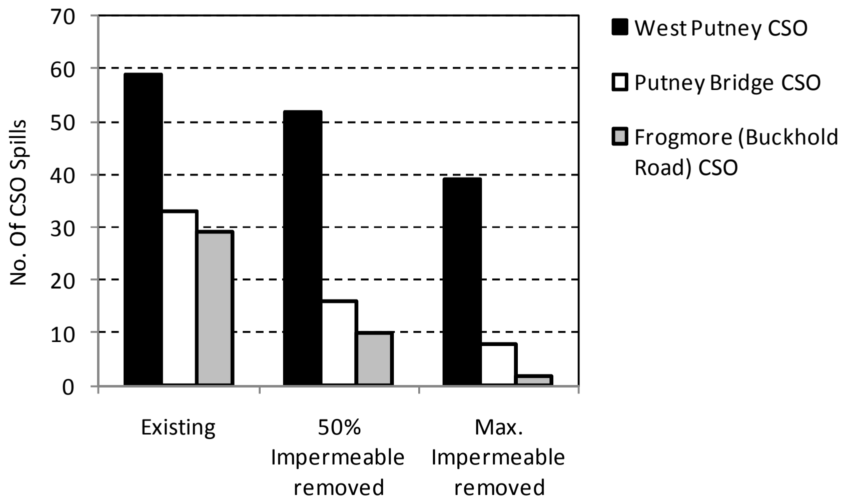

Figure 5 Number of spills associated with the typical year event for selected disconnection scenarios

The impact of removing 50% impermeable area was also assessed for the entire system. The number of individual CSOs producing overflow during the typical year reduces from 32 to 22, and the total overflow volume reduces by 54%. This would, it should be noted, be contingent on the disconnection of about 10,300 ha of impermeable area. This is equivalent to approximately 15,000 football pitches (0.7 ha) or 1.5 million typical house roofs (70 m^2).

Maximum practical disconnection scenarios

In general the maximum 'practical' scenarios produced better performance outcomes than the 50% global disconnection scenarios because they disconnect approximately 75% of impermeable area into permeable, initial loss and storage areas. For example, total overflow volume reductions were 49%, 70% and 83% at West Putney, Putney Bridge and Frogmore respectively for the October 2000 event. The December event did not generate any spill at either Putney Bridge or Frogmore, although other events with different rainfall characteristics mean that spills are not completely eliminated from any of the CSOs in a typical year. The number of spills in a typical year at the Frogmore CSO was reduced to 3 (-90%), with the total volume being only 400 m^3 (1% of the existing situation). This would imply that this level of SuDS retrofitting would provide sufficient CSO control. However, the number of CSO events remains high at West Putney and Putney Bridge, and SuDS alone may not provide sufficient CSO control to eliminate the need for additional CSO control facilities in these catchments.

Discussion

Refined approach – Final disconnection scenarios

The initial preference rankings for retrofit options (Table 2) were based on hydraulic performance only; other factors – such as cost (initial capital and operation and maintenance), who pays, public and planning acceptability, environmental and social cost/benefit – were not taken into account. A further, final, iteration was therefore undertaken to generate more 'realistic' options. The key refinements were associated with: i) the identification of 'easy-pickings' of larger housing complexes (such as municipal housing estates); and ii) a more realistic assessment of the 'likely' implementation of SuDS for the remaining catchment land-uses.

Municipal Housing Areas

During a site visit to the West Putney, Putney Bridge and Frogmore (Buckhold Road) subcatchments in May 2009, it was noted that there were large proportions of municipal housing within the catchments, especially Frogmore (Buckhold Road) and West Putney. These areas are characterised by large, often flat roofed buildings set in large communal gardens. It was believed that these areas had the potential to exploit a type of retrofit SuDS approach which had not fully been considered in the earlier optioneering and generation of preferences. Lambeth Council (2011) have already shown the feasibility of implementing extensive green roof retrofits to municipal housing in a comparable location. The approach was more regional in nature, being based on detention ponds and swales and utilizing communal green spaces. Detailed designs undertaken for selected representative land-use distributions suggested that 100% diversion from existing impermeable surfaces could be achieved. Not only could high levels of disconnection be achieved, the potential to use treatment trains and high amenity-value SuDS (such as rain gardens) makes these options particularly attractive. The buildings are also likely to be of single or not too many individual ownerships, which is more practical for implementation.

Notwithstanding the integration of these new disconnection scenarios within the final refined catchment-scale retrofit evaluation, the authors recommend that this type of area would also be highly suitable for a pilot-scale implementation project – a proposal endorsed by the previously-cited existing examples from Malmö and Lambeth.

Implementation

During evaluation of the refined disconnection scenario, it was recognised that many of the identified options – though technically feasible – could not realistically be expected to be implemented in an appropriate time-scale for UWWTD compliance, due to reasons of cost, planning authority, acceptability, or engineering complexity. The degree of implementation, or uptake levels, was therefore introduced to reflect the expected realistic level of implementation within a short- to medium-term time scale. The revised implementation levels included, for example, an estimated uptake level for the replacement of road surfaces with permeable surfaces of 0% (that is, permeable road surfaces are not expected), but an expectation that 40% of road drainage might be diverted to adjacent permeable surfaces.

Assessment of the refined disconnection scenarios

The refinements outlined above were used to generate a revised estimate of the level of impermeable area disconnection that might be achieved. Areas of suitable municipal housing were manually identified from the MasterMap data, and treated in isolation from the remaining area in each sub-catchment. The refined disconnection strategy corresponds to approximately 37% removal of the existing impermeable area, with the disconnected flows being diverted to a mixture of initial loss, permeable area and storage attenuation. Given that none of the impermeable area is completely disconnected, this suggests that a reasonable estimate of the system response would correspond to the mid-point between the 25% and 50% global scenarios for which disconnected flows were re-routed onto permeable areas. The result has been a significant downward revision of the potential for disconnection of the existing impermeable areas, which results in a much poorer relative performance as regards CSO operation when compared to the maximum practical disconnection scenarios. This revised, but what is believed to be more practicable, disconnection rate needs to be re-tested using the catchment hydraulic model, however it was concluded that since the most receptive of the three subcatchments, Frogmore (Buckhold Road), was shown by modelling to spill too often in a typical year to meet the requirements of the UWWTD when the impermeable area was reduced by 50%, the refined disconnection scenario with 37% removal of impermeable area would therefore also not meet the requirements of the UWWTD.

Cost-Benefits

The whole-life costs of disconnection has been evaluated and found as a minimum to be of the order of £20-£59 million in each subcatchment for a design life of 50 years. The report proposes piloting of retrofit SuDS through municipal housing areas. Specific designs and costings have been undertaken, which suggest that municipal housing areas provide a relatively practical and cost-effective option (compared with other land-uses) at some £12.70 per m^2 disconnected impermeable area.

There are considerable added benefits in using SuDS instead of piped/sewered drainage systems, including improvements to water quality; amenity, quality of urban spaces and ecological benefits and greater resilience to climate change (Ashley *et al.*, 2011). None of these were quantified in the study as it was outside the original brief; i.e. although the costs were considered reasonably well defined, many of the potential benefits were not assessed.

Barriers to implementation and the benefits of an incremental and complementary approach

Disconnecting 50% of the impermeable area from the entire LTT catchment would reduce the total overflow volume by 54%. However, this represents the disconnection of approximately 10,300 ha of hard surfaces such as roofs, drives, car parks, roads and pavements. This is a considerable amount, equivalent to approximately 15,000 football pitches. There are many difficulties in implementing SuDS across the borough boundaries of London. These include legal and regulatory problems in regard to who has the authority to require or implement SuDS, and the transfer of ‘ownership’ of the redirected stormwater to the myriad property and land owners and road and highway operators. Many of these stakeholders do not have the experience and hence the capacity to take on this responsibility and would need to be assisted by local authorities or water companies to develop this capacity. Such an approach is much more straightforward in the USA where responsibilities for stormwater runoff and CSO controls generally rest with a City, State or Federal agency. In Philadelphia for example, the Mayor is responsible for the entire range of public services, including roads, water supplies, sewerage, parks, welfare and health. Hence if the Mayor of London can identify the full range of direct and indirect benefits to the City from disconnecting stormwater, then implementation may be more straightforward. Indirect benefits could include reductions in heat island problems, resulting in reduced health problems and less air conditioner use in the summer, improvements to the City's liveability and increase in property values.

In the UK, as elsewhere, urban redevelopment provides a significant opportunity to incrementally implement a more sustainable and adaptable green infrastructure philosophy of stormwater management through the implementation of (retrofit) SuDS. It may be desirable to consider redevelopment as 'new build' and to apply far more stringent SuDS requirements rather than the 'like-for-like' surface runoff control. The scale of redevelopment is such that in many urban areas such an approach might transform the drainage characteristics of up to 10% of urban cores over a period of 10 years. Many (retrofit) SuDS options are fully compatible with the EU ecosystem services policy document (European Commission, 2011) that aims to increase our green areas by 15% by 2015.

Conclusions

A two-stage assessment process has been developed for evaluating the potential to retrofit SuDS to address a specific stormwater management need (in this case combined sewer overflow control) at the catchment scale:

i. Global disconnection scenarios enable a rapid assessment to be made of **what might be achieved** with various levels of disconnection, based on mapping of land-uses and catchment hydraulic modelling.
ii. For the second stage an automated GIS-based tool has been developed that enables retrofit SuDS **options to be identified and prioritised**, and recommendations for the representation of proposed retrofits for catchment hydraulic modelling have been made.

There is considerable scope for further development of the GIS-based retrofit SuDS option development tool. In particular, it tends to focus on single, source control measures, whereas in many contexts site or regional-scale controls may be more feasible and SuDS treatment trains would be preferable from a water quality perspective.

In the context of the catchment studied, the data and analysis suggest that high levels of disconnection are technically possible, although practicably difficult to implement, retrofit SuDS would be a form of additional overflow control for these CSOs. Given that these subcatchments were selected on the basis of their favourability, the potential to address CSOs in other subcatchments is probably considerably less.

Significant uncertainties surround the estimation of costs associated with large-scale SuDS retrofit, whilst the levels of disruption associated with their implementation may be considered too prohibitive for rapid large-scale implementation. Although the direct and indirect benefits potentially associated with the use of retrofit SuDS as a component of urban greening are increasingly recognised, the conflict between those who stand to benefit (the broader public) and those expected to pay (local authorities and water utility customers) means that implementation is a real challenge in the UK. Retrofit SuDS may be best seen as providing a complementary approach to conventional sewer rehabilitation measures, and opportunities should be taken to implement them incrementally, in association with progressive urban renewal, as is being done in many cities in the USA. The development of selected pilot-scale implementations in the UK focusing on public housing and roads is particularly recommended to demonstrate the benefits, costs and implementation challenges.

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