A GIS-based methodology for selecting stormwater disconnection opportunities

S. L. Moore, V. R. Stovin, M. Wall and R. M. Ashley

ABSTRACT

The purpose of this paper is to introduce a geographic information system (GIS)-based decision support tool that assists the user to select not only areas where (retrofit) sustainable drainage systems (SuDS) could be implemented within a large catchment (>100 ha), but also to allow discrimination between suitable SuDS techniques based on their likely feasibility and effectiveness. The tool is applied to a case study catchment within London, UK, with the aim of increasing receiving water quality by reducing combined sewer overflow (CSO) spill frequency and volume. The key benefit of the tool presented is to allow rapid assessment of the retrofit SuDS potential of large catchments. It is not intended to replace detailed site investigations, but may help to direct attention to sites that have the greatest potential for retrofit SuDS implementation. Preliminary InfoWorks CS modelling of 'global disconnections' within the case study catchment, e.g. the removal of 50% of the total impervious area, showed that CSO spill volume could be reduced by 55 to 78% during a typical year. Using the disconnection hierarchy developed by the authors, the feasibility of retrofit SuDS deployment within the case study catchment is assessed, and the implications discussed.

Key words | CSO, GIS, retrofit SuDS, stormwater disconnection

S. L Moore (corresponding author)
V. R Stovin
R. M Ashley
Pennine Water Group,
Department of Civil and Structural Engineering,
University of Sheffield S1 3JD,
UK
Email: *s.moore@sheffield.ac.uk*

M. Wall
Halcrow Group Ltd,
Elms House,
43 Brook Green,
London, W6 7EF,
UK

INTRODUCTION

The potential benefits of utilising sustainable drainage systems (SuDS) (also known varyingly as Low Impact Development, Water Sensitive Urban Design and Best Management Practices in the USA, Australia and mainland Europe, respectively) within urban areas to address water quality, quantity and amenity are well known. However, despite these known benefits, to date, most SuDS schemes within the UK are associated with new build areas. New build areas comprise a small proportion of the total urban area within the UK, which implies that the full potential of SuDS has not yet been exploited. The term Retrofit SuDS is used when SuDS are used to replace or augment an existing drainage system within a developed catchment. Examples of retrofit SuDS could be the installation of a green roof, the diversion of roof drainage from a combined sewer system to a garden soak-away, or the conveyance of road runoff via swales into a pond located in adjacent green space.

Retrofit SuDS are useful tools to achieve more holistic management of urban stormwater. Currently the main drivers for stormwater disconnection implementation may be: water quantity reduction, by reducing runoff from impervious areas; or water quality improvements, either through the reduction of the frequency or volume of combined sewer overflows (CSO) or storm sewer outfalls (SSO) or by reducing diffuse urban pollution runoff from urban areas. In the future, retrofit SuDS may also be used when amenity benefits, such as reduction of urban heat island effect, or biodiversity enhancement, are required.

Commercially available urban stormwater models such as SWMM, InfoWorks and WinDes are widely available. For detailed reviews of these models, see Elliott and Trowsdale (2007) or Yang & Wang (2010). While these models are well placed to model the hydrological and/or water quality performance of SuDS structures at the site or neighbourhood scale, due to their complexity, they would not be suitable in the modelling of large (city) scale stormwater disconnection. A notable exception is the US EPA model System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) (Lai *et al.* 2007; Shoemaker *et al.* 2009), which combines a decision support system to select the most appropriate SuDS within a

doi: 10.2166/wst.2012.172

catchment with SWMM and the Hydrological Simulation Program in FORTRAN (HSPF) to enable the hydrological and water quality performance to be analysed, as well as allowing a comparison of capital costs between options. However, the model is fairly data intensive to operate.

There are presently few established approaches to the selection of SuDS options for retrofitting on a widespread scale. Published applications to date have related predominantly to local interventions, for example rain gardens (Smith *et al.* 2007) or Street Edge Alternatives (SEA) streets (Seattle Government 2009), although guidance on retrofits for the reduction of CSO spills is available (e.g. Weinstein *et al.* 2006, 2009). However, in order to be effective, larger scale implementation should be considered. Several decision support systems have been developed in order to assist in the selection and implementation of SuDS. Many of these approaches utilise a matrix structure to score the SuDS options based on a number of criteria (technical, environmental, social, and economic) for example, Swan & Stovin (2002), Ellis *et al.* (2005), Martin *et al.* (2007) and Scholz (2006).

An approach developed by Swan & Stovin (2002) and further refined by SNIFFER (2006) was initially used in order to prioritise disconnection options for the reduction of CSO spill frequency. The framework embodies three hierarchies (see Table 1), 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. The full decision support flowcharts can be downloaded from http://retrofit-suds.group.shef.ac.uk/publications.html.

A key benefit of the SNIFFER (2006) approach is that the hierarchy can easily be modified depending on the specific driver for retrofitting SuDS within the catchment of interest. However, in order to implement the hierarchy at a large scale, significant amounts of data are required, some of which, for example, land/building ownership, may be difficult to obtain. However, in order to meet water management challenges that the future might bring, it is important to move away from small scale implementation of SuDS.

Geographic information system (GIS)-based decision support tools have been developed to allow the combination of urban stormwater models such as those described above, with decision support systems to provide a more user-friendly representation of the modelling outputs (e.g. Lai *et al.* 2007, Viavattene *et al.* 2008, 2010 and Cheng *et al.* 2009). 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 purpose of this paper is to introduce a simple GIS-based methodology that allows the user to rapidly assess the likely retrofit SuDS potential of large catchments. It is not intended to replace detailed site investigation, rather it allows assessment at the master-planning level, and may assist Local Authorities or planners to prioritise areas for SuDS deployment within a catchment. The tool utilises readily available data to produce maps highlighting areas in which retrofit SuDS are feasible, based on a series of predetermined, modifiable rules and the SNIFFER (2006) hierarchy. Subsequent hydraulic/water quality modelling of each catchment using InfoWorks CS allows the user to estimate the likely ability of the proposed disconnection scenarios to meet pre-defined targets, for example, CSO spill

Table 1 | Retrofit SuDS disconnection framework (after SNIFFER 2006)

Increasing complexity in terms of design work required

	Urban surface type		**Surface water management train**	**Mode of operation**
Decreasing practicality of implementation	Publicly owned	Large (>200 m²) roofs	Source control	Retention at source
		Car parks	Conveyance and offsite control	Infiltration
		Highways		Disposal
	Privately owned	Large roofs		Storage
		Car parks		Reuse
		Residential roofs		

frequency, and also allows the comparison between other methods proposed to manage stormwater on the site.

IDENTIFICATION OF RETROFIT SuDS LOCATIONS

The GIS package ArcView v9.3 has been used within this study. A series of logic-based Structured Query Language (SQL) rules have been set up within the 'Model Builder' module of ArcView. 'Search by Attributes' and/or 'Search by Location' are used to select parcels of land that are deemed suitable for a specific retrofit SuDS option based on their physical characteristics and/or spatial location. The perceived suitability of each retrofit SuDS option generated for each parcel of land can subsequently be determined using a combination of design guidance (e.g. Woods-Ballard *et al.* 2007; Weinstein *et al.* 2009) and expert judgement. A key benefit of this approach is that the process can be automated, allowing large datasets to be processed rapidly, and with minimal data preparation. SQL queries can be linked to multiple datasets, such as geology and Digital Terrain Models (DTM) to further refine the accuracy of the predictions.

The initial dataset used to select the retrofit SuDS potential was OS MasterMap, commercially available from the Ordnance Survey within the UK. For urban areas, OS MasterMap is available at 1:1,250 scale and comprises: topography data (vector data that represents physical objects such as buildings and roads as well as intangible objects such as administrative boundaries); integrated transport network (ITN) data and address data (the latter is available at additional cost). Each feature within the OS MasterMap dataset has a unique identifier, which allows linkage with any other dataset, making OS MasterMap an ideal base layer. For the purposes of this paper, references to OS MasterMap, are concerned with the Topography data only.

Table 2 | Retrofit options considered for roofs, car parks/hardstanding and roads, and the selection process employed within ArcView

OS MasterMap surface and retrofit SuDS options	Process used to select the parcel of land within ArcView
Roofs	
1. Green roofs on suitable buildings (<30° slope)	Manual digitisation of flat roofs using aerial photography. GIS used to select roofs >200 m^2. Engineering judgement is used to select buildings with likely suitable load bearing capacity.
2. Disconnect large public or privately owned buildings to adjacent pervious land	Select buildings >200 m^2 from OS MasterMap. If available, use in conjunction with Address data, e.g. OS AddressLayer2 to discriminate between publically owned and privately owned buildings.
3. Disconnect domestic roofs to adjacent greenspace/soakaway	A statistical evaluation of the total footprint area of buildings and their associated gardens. Gardens were selected that were > building footprint area. Gardens were assumed to have a suitable degree of perviousness.
4. Water butts/rainwater tanks	Water butts/rainwater tanks were considered for properties where garden area > roof area, but when soakaways are not permissible due to site specific factors such as unfavourable infiltration rates.
Car parks	
1. Permeable surfacing	Manmade land was selected from MasterMap. Those >200 m^2 (arbitrary area below which was not deemed cost effective to re-surface).
2. Disconnect to adjacent pervious land	Areas of manmade land within a distance (1 m) of natural land.
3. Offsite local detention and swale conveyance	Selection of areas of natural land within 10 m of hard standing.
Roads	
1. Replace with pervious surfacing	Access roads (with low levels of traffic) selected using local knowledge in the absence of suitable data.
2. Street edge alternative (SEA) streets/ disconnect to pervious	Roads >10 m width (surrogate for A and large B roads), and additional roads manually selected using local knowledge of areas where traffic calming is considered.
3. Pocket street infiltration	Selection of roads within 2 m of natural land (>100 m^2 in order to ensure that areas are large enough to take the road runoff).
4. Off-site local detention and swale conveyance	Selection of areas of natural land within 10 m of roads.

Logic based, spatial selection of land parcels using GIS

Several generic land-use types are present within OS MasterMap. 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'. Retrofit SuDS options, as well as examples of the SQL criteria applied to determine feasibility are shown in Table 2.

Generating retrofit SuDS options

The spatial selection of land parcels described above generates multiple layers indicating locations where each specific retrofit SuDS measure may be feasible. However, in many cases, more than one option may be feasible in any given location. It is therefore necessary to rank each option according to a set of preferences. The preferences may vary depending on site specific constraints, or through specific legislative constraints. Within this paper, the SNIFFER (2006) hierarchy presented in Table 1 has been used to choose the most suitable option, with options selected based on their potential applicability and hydraulic effectiveness. For example, source control measures, have precedence over regional or offsite measures, and publically owned or large, single owner buildings are judged more amenable to retrofit than domestic buildings.

Hydrological modelling

InfoWorks CS v9.5.3 was selected as the software package within this study in order to allow the retrofit SuDS disconnection scenarios generated to be compatible with additional, hard engineering, solutions that were being generated in parallel with this study.

Workflow of methodology

An overview of the methodology used within this study is presented in Figure 1.

APPLICATION: LONDON CASE STUDY

Three neighbouring CSO Catchments within west London were selected for this study based on their perceived likelihood of SuDS feasibility (Figure 2). These are: Frogmore (Buckhold Road); West Putney and Putney Bridge. Frogmore (Buckhold Road) comprises 454 ha mixed-use urban area, West Putney and Putney Bridge catchments are 425 and 142 ha respectively.

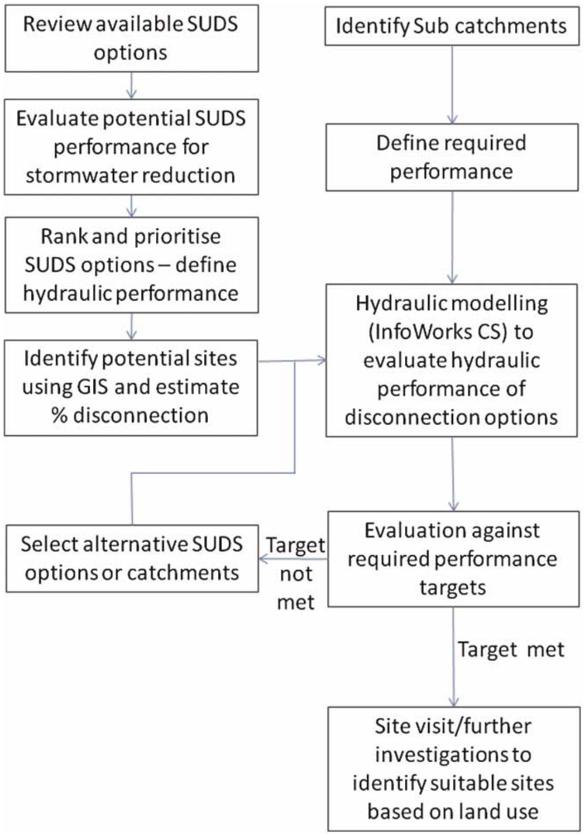


Figure 1 | Workflow of the methodology used to select retrofit SuDS opportunities (after Ashley *et al.* 2010).

Each of the case study catchments are located within the Thames Tunnel (TT) catchment. The TT has been designed to significantly reduce the spill flows from CSOs and pumping stations within the River Thames. The planned intervention strategy to deliver the flows into the tunnel has, in many cases, resulted in costly diversion structures being proposed. However, in some cases the volumes and magnitudes of the spilled flow are relatively small. This has raised questions as to whether the introduction of SuDS could see a potential benefit in the reduction of the spilled flow. Several other potential interventions to manage CSO spills have also been considered (Thames Water 2010). Currently, the TT proposals are undergoing public consultation.

Preliminary InfoWorks modelling: global disconnections

In order to test whether disconnection of stormwater inputs to the sewer network could potentially be useful,

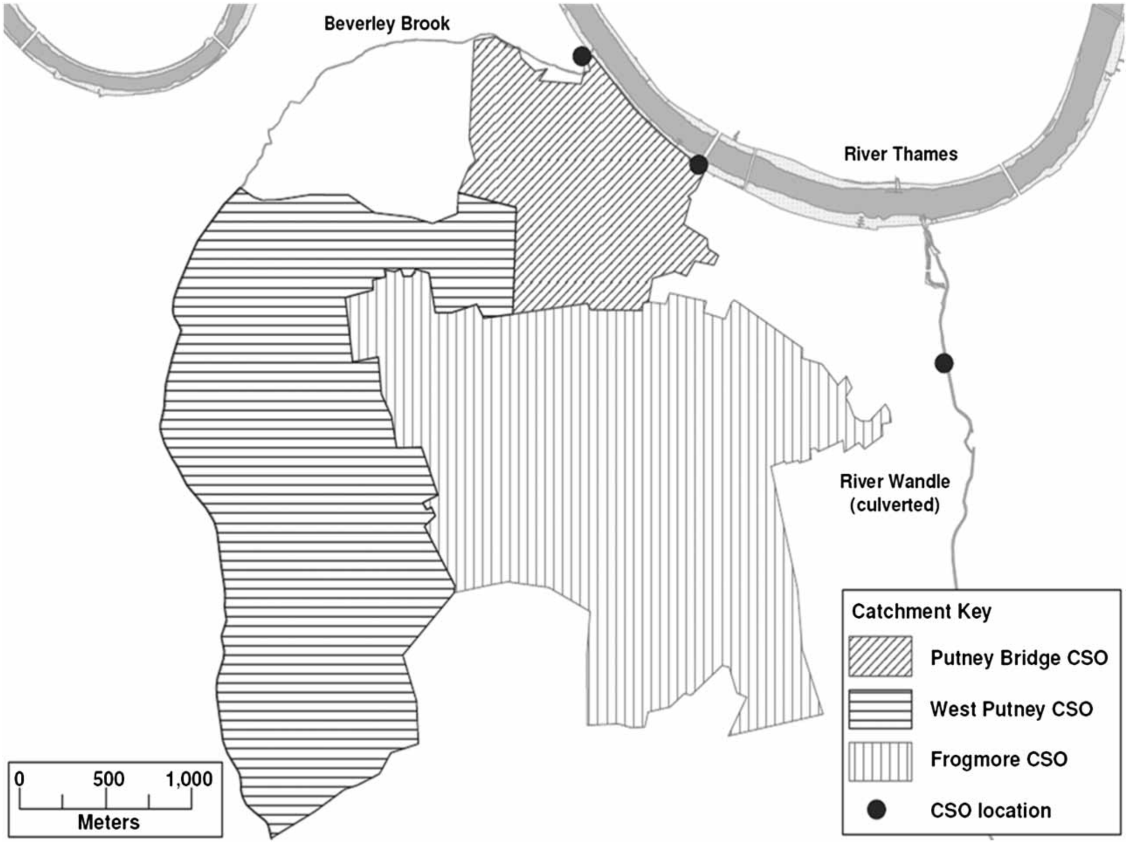


Figure 2 | Location of the three CSO subcatchments investigated. © Crown Copyright/Digimap 2011. An Ordnance Survey/EDINA supplied service.

initial, 'global' disconnection figures were modelled within InfoWorks CS v9.5.3. The model subcatchments for each of the three CSOs were adjusted to provide an initial evaluation of global SuDS' impacts on peak flow and CSO volume for the October 2000 (1 in 4 yr return period, peak intensity 23.6 mm/h) event. This event was selected as it represents the most severe recorded rainfall events for the Summer Compliance Test Procedure (CTP) rainfall event series. The simulations carried out were as follows: 50% impermeable area transferred to permeable area; 50% impermeable area removed and 5 mm rainfall removed from the beginning of the storm. Fifty per cent was selected as a bench mark as it was deemed the upper end of what would be feasible to disconnect within the system. By transferring impermeable area to permeable, some attenuation and initial losses will be achieved; however, runoff remains connected to the sewer network. The removal of impermeable area represents a situation in which the area is no longer connected to the sewer network. Finally, removing 5 mm rainfall from the beginning

Table 3 | CSO performance improvements associated with 50% area change for the October 2000 rainfall event

	Maximum flow, m^3/s *(% change)*			**Average flow during event, m^3/s *(% change)***			**Total overflow volume, m^3 *(% change)***		
	A[a]	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
Frogmore (Buckhold Rd)	3.03	1.88 *(−38%)*	1.63 *(−46%)*	0.39	0.23 *(−41%)*	0.19 *(−52%)*	17,700	6,500 *(−63%)*	4,700 *(−73%)*
West Putney	0.93	0.65 *(−30%)*	0.52 *(−44%)*	0.18	0.14 *(−22%)*	0.12 *(−33%)*	13,900	10,800 *(−22%)*	8,300 *(−40%)*
Putney Bridge	2.61	2.04 *(−22%)*	1.96 *(−25%)*	0.35	0.27 *(−23%)*	0.26 *(−26%)*	9,100	4,400 *(−52%)*	3,600 *(−60%)*

[a] A, existing system; B, 50% impervious area transferred to permeable; C, 50% impervious area removed.

of the storm is representative of a local storage system (e.g. green/blue roof).

From Table 3 it can be seen that that Putney Bridge and Frogmore subcatchments show particularly promising results for the potential disconnection, with the Frogmore catchment experiencing a predicted 73% decrease in spill volumes for the October 2000 rainfall event.

Application of the disconnection methodology: InfoWorks modelling of stormwater disconnection options generated for each subcatchment

Due to the size of the TT catchment, it is not practical to model each individual sewer and pipe length within the entire catchment. The smallest diameter pipe modelled was 375 mm. SuDS units, especially those used for source control, operate at a very local scale. Therefore caution is required when using large scale models to represent SuDS. Within this study, no attempt has been made to model the SuDS units themselves; rather their effects in terms of changing stormwater runoff and input to the sewer network have been modelled using the assumptions presented in Table 4. The preference order for SuDS disconnection options shown in Table 4 has been applied whenever more than one disconnection option was technically viable. For this study, source control options alone are applied.

Some of the retrofit SuDS options were assumed to offer rainfall retention, which was represented in the hydraulic

Table 4 | Potential retrofit SuDS options for each surface type and indicative hydraulic modelling approach

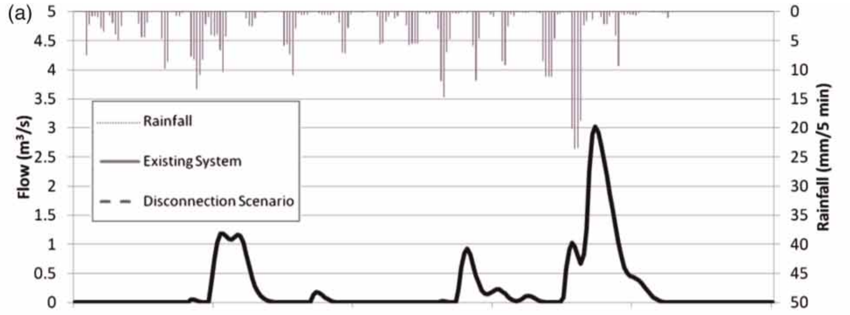
Primary SuDS options and preference order	Hydraulic modelling approach
Roofs	
1. Disconnect to garden soakaways	Complete removal of area from network
2. Disconnect to lawns	Initial losses (25 mm)
3. Water butts	Initial losses (25 mm) (if oversized cistern specified)
4. Green/blue roofs	Initial losses (25 mm), Transfer impermeable area to pervious (modifications to pervious store)
Non-road hardstanding (inc. car parks)	
1. Permeable surface	Initial losses (25 mm), storage/attenuation
2. Disconnect to adjacent pervious	Transfer impermeable area to permeable
3. Offsite – local detention	Storage/attenuation
Other manmade surfaces	
1. Disconnect to adjacent pervious	Initial losses (25 mm), storage/attenuation
Roads	
1. Permeable surface	Initial losses (25 mm), storage/attenuation
2. Disconnect to adjacent pervious/SEA streets	Transfer impermeable area to permeable
3. Pocket street infiltration	Initial losses (12 mm)
4. Offsite – detention and swale conveyance	storage/attenuation

Table 5 | Impact of stormwater disconnection methodology on permeability for each subcatchment

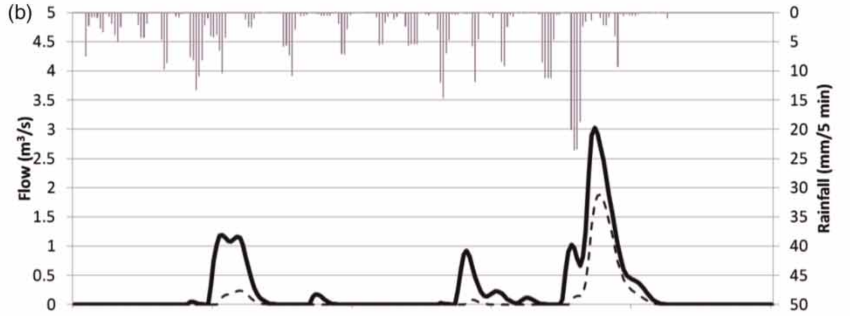
	West Putney		**Putney Bridge**		**Frogmore (Buckhold Road)**	
	A	**B**	**A**	**B**	**A**	**B**
% Impermeable	12	3	45	9	36	9
% Permeable	42	44	55	65	48	56
% Impermeable with initial losses	–	1	–	8	–	4
% Impermeable with storage	–	5	–	18	–	17

A = Existing scenario, B = stormwater disconnection scenario. Note, totals do not equal 100 as some areas are not connected to the system.

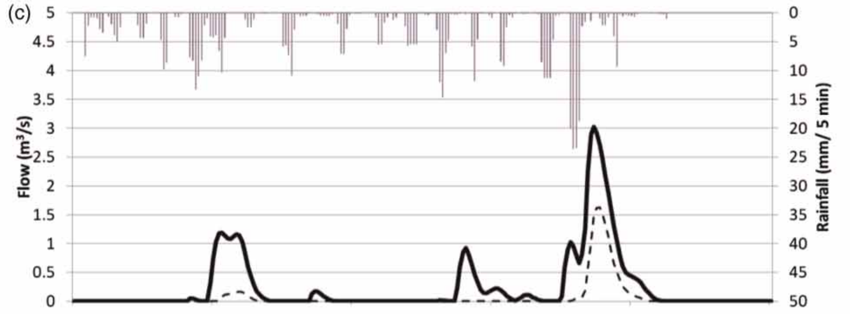
model using 25 mm initial losses. The focus of this paper is not on either the expected hydraulic performance of specific SuDS devices; nor is it a detailed investigation of how such devices could or should be represented in InfoWorks. Important questions, such as the available storage at the start of the storm event, were not explicitly considered, and this is clearly



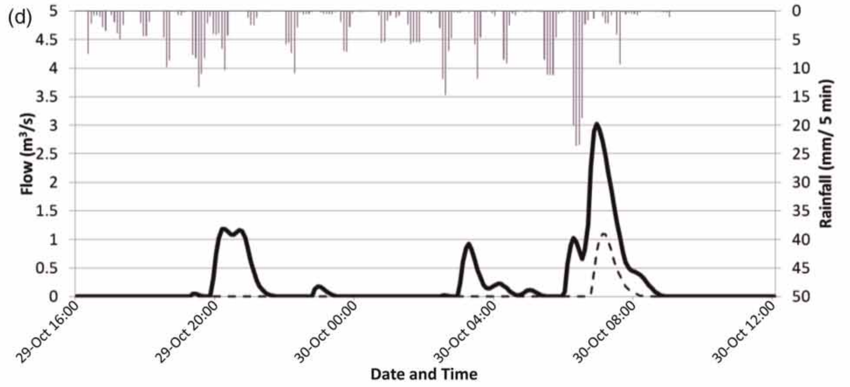
5 mm initial losses 'global disconnection scenario'



50 % of impermeable area converted to pervious 'global disconnection scenario'



50 % of impermeable area removed 'global disconnection scenario'



Application of stormwater disconnection options identified

Figure 3 | Modelled CSO flow at Frogmore Buckhold Road during the October 2000 event.

an area that will receive greater attention in the future. As an interim measure, 25 mm was selected as a ‘standard’ initial losses depth for retrofit SuDS devices. This may be visualised as representing, for example: the direct retention of the first 25 mm of a rainfall event by an intensive (deep) green roof, or a blue roof; an oversized water butt (0.875 m^3) would retain 25 mm rainfall from 50% of a typical 70 m^2 house roof (assuming only the rear half was disconnected); a permeable pavement with a storage depth of 360 mm and a voids ratio of 0.3, equates to 108 mm retention. However, assuming that the pavement was used to drain adjacent impermeable areas in addition to its own surface, this retention depth would reduce proportionately. A measure of 25 mm represents a total catchment area approximately 4.3 times the area of the permeable pavement.

Table 5 shows the impact of the stormwater disconnection methodology on the relative percentages of permeable and impermeable areas within each CSO subcatchment. In most cases, a significant difference can be observed.

RESULTS

From Figure 3 and Table 6, it can be seen that, while it was not possible to completely eliminate CSO spills within each subcatchment, marked improvements to the existing system can be achieved. Indeed, in general, the disconnection scenarios produced better performance outcomes than the 50% global disconnection scenarios. For example for the Frogmore (Buckhold Rd) catchment, the catchment with the greatest reduction in runoff, a 67% reduction in peak flow rate can be achieved, compared with a 34% reduction for the 50% global disconnection scenario (Figure 3). However, in order to achieve this improvement, a significant level of surface disconnection would be required, which is unlikely to be technically feasible.

Further refinements

For this study, source control SuDS options alone were considered. ‘Regional’ controls (Woods-Ballard *et al.* 2007) such as storage ponds, could also be specified, which would allow runoff to be collected from a series of contributing areas and would therefore potentially provide greater levels of attenuation. The disconnection scenarios presented were further refined to reflect opportunities likely to be cost-effective and acceptable to relevant stakeholders, although no modelling of these options was undertaken. The methodology is currently being further refined as part of the EPSRC funded URSULA (Urban River corridors, SUstainable Living Agendas) project.

Table 6 | CSO performance improvements associated with the stormwater disconnection options generated for the October 2000 rainfall event

	Spill Volume (m^3) (% *change from existing*)
Frogmore (Buckhold Road)	2,500 (−*86*)
West Putney	6,000 (−*57*)
Putney Bridge	2,300 (−*75*)

CONCLUSIONS

In order to retrofit SuDS options at a large (catchment) scale, automated GIS-based tools combined with a preference hierarchy are invaluable. The application of the hierarchy to the three subcatchments in general produced better performance outcomes than the 50% global disconnection scenarios. While the deployment of retrofit SuDS alone would not completely provide the required reduction in CSO spill frequency/volume, they could be used in conjunction with other capital investments to form a hybrid solution. The methodology presented currently comprises a fairly crude selection of land uses. By utilising a larger number of datasets (combining geological data, topography or address information), the reliability of the selections would be increased.

ACKNOWLEDGEMENTS

Work was funded by H2CM Hill on behalf of Thames Water and continues through the URSULA project, funded by the UK Engineering and Physical Sciences Research Council (Grant number: P/F007388/1). The authors are grateful for this support. The views presented in the paper are those of the authors and cannot be taken as indicative in any way of the position of the funders or of colleagues and partners. Any remaining errors are similarly those of the authors alone.

REFERENCES

Ashley, R., Stovin, V., Moore, S., Hurley, L., Lewis, L. & Saul, A. 2010 London Tideway Tunnels programme. Thames tunnel project needs report. Potential source control and SUDS options: Land use and retrofit options. Needs Report Appendix E. 100-RG-PNC-00000-900008. Available from: http://www.thamestunnelconsultation.co.uk/consultation-documents.aspx (accessed 9 February 2012)

Cheng, M. S., Zhen, J. X. & Shoemaker, L. 2009 BMP decision support system for evaluating stormwater management alternatives. *Front. Environ. Sci. Engin. China* **3** (4), 453–463.

Elliott, A. H. & Trowsdale, S. A. 2007 A review of models for low impact urban stormwater drainage. *Environ. Modell. Softw.* **22**, 394–405.

Ellis, J. B., Deutsch, J. C., Legret, M., Martin, C., Revitt, D. M., Scholes, L., Seiker, H. & Zimmerman, U. 2005 The Day Water decision support approach to the selection of sustainable drainage systems: a multi-criteria methodology for BMP decisions. In: *10th International Conference on Urban Drainage*, 21–26th August 2005, Copenhagen, Denmark.

Lai, F., Dai, T., Zhen, J., Riverson, J., Alvi, K. & Shoemaker, L. 2007 SUSTAIN- An EPA BMP process and placement tool for Urban Watersheds. In: *Proceedings of the Water Environment Federation*. TMDL, pp. 946–968.

Martin, C., Ruperd, Y. & Legret, M. 2007 Urban Stormwater Drainage management: the development of a multi-criteria decision aid approach for Best Management Practices. *Eur. J. Oper. Res.* **181**, 228–349.

Scholz, M. 2006 Decision support tools for sustainable drainage. *Proceedings of the Institute of Civil Engineers–Engineering Sustainability* **159** (issue ES3), 117–125.

Seattle Government 2009 Street Edge Alternatives (SEA streets) project. Available from: http://www.seattle.gov/util/About_SPU/Drainage_&_Sewer_System/Natural_Drainage_Systems/Street_Edge_Alternatives/SPU_001805.asp (accessed 10 July 2009).

Shoemaker, L., Riverson, J., Alvi, K., Zhen, J. X., Paul, S. & Rafi, T. 2009 SUSTAIN, A framework for the placement of Best Management Practices in Urban Watersheds to Protect Water Quality. USEPA Report EPA/600/R-09/095. Available from: www.epa.gov (accessed January 2012).

Smith, N., Allen, R., McKenzie-McHarg, A., Deletic, A., Fletcher, T. D. & Hatt, B. E. 2007 Retrofitting Functioning Stormwater Gardens Into Existing Urban Landscapes, *Cairns International Public Works Conference*, Cairns, August 2007, Australia.

Swan, A. D. & Stovin, V. R. 2002 A decision-support framework for the design of retrofit SUDS. In: *Proceedings of the International Conference on Sewer Operation and Maintenance (SOM2002)*, 26–28 November, University of Bradford.

SNIFFER 2006 Retrofitting Sustainable Urban Water Solutions. Project UE3(05)UW5. Report available from: www.sniffer.org.uk (accessed 2 November 2011).

Thames Water 2010 Needs Report. Report 100-RG_PNC_00000_9007. Summer 2010. Report available from: http://consense.opendebate.co.uk (accessed 2 November 2011).

Viavattene, C., Scholes, L., Revitt, D. M. & Ellis, J. B. 2008 A GIS based decision support system for the implementation of Stormwater Best Management Practices. In: *11th International Conference on Urban Drainage*, Edinburgh, Scotland.

Viavattene, C., Ellis, J. B., Revitt, M., Seiker, S. & Peters, C. 2010 *The Application of a GIS-based BMP Selection Tool for the Evaluation of Hydrologic Performance and Storm Flow Reduction*. Novatech 2010, Session 3.2, pp. 1–10.

Woods-Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R. & Shaffer, P. 2007 *The SUDS Manual*. CIRIA C697. London.

Weinstein, N., Glass, C., Heaney, J. P., Gwang Lee, J., Huber, W. C., Jones, P., Kloss, C., Quigley, M., Strecker, E. & Stephens, K. 2006 *Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction*. WERF. IWA Publishing, London, Chapter 4.

Weinstein, N., Cotting, J., Nees, D., Downing, S., Lee, J., Tauber, B., English, A., Kloss, C., Glass, C., Huber, W. C. & Morgan, T. 2009 *Decentralized Stormwater Controls for Urban Retrofit and Combined Sewer Overflow Reduction, Phase II*. WERF. IWA Publishing, London, Chapters 3 and 5.

Yang, Y. S. & Wang, L. 2010 A review of modelling tools for the implementation of the EU Water Framework Directive in handling Diffuse Water Pollution. *Water Res. Manage.* **24**, 1819–1843.

First received 9 November 2011; accepted in revised form 22 February 2012