Whole Life Costs and Benefits of Sustainable Urban Drainage Systems in Dunfermline, Scotland

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Abstract

Sustainable urban drainage systems (SUDS) are increasingly prominent as a solution to many of the performance and environmental problems associated with traditional drainage systems. Questions remain regarding the values of maintenance costs and environmental benefits delivered throughout the useful lives of SUDS. Using the Dunfermline East Expansion area in Scotland as a case study, this study represents a novel approach in that it collects actual maintenance data, assesses ecosystem services, and carries out whole life cost analyses. Findings suggest that SUDS may be accounted as a net asset, although assumptions inherent to ecosystem services assessment methodologies produce a wide range of uncertainty.

Keywords

SUDS, ecosystem services, traditional drainage, operational and long-term maintenance costs, whole life costs, decision support tools, Scotland.

Introduction

Flooding, impaired water quality, and biodiversity loss are common consequences of traditional urban stormwater management practices (Duffy et al., 2008; Marlow et al., 2013). Due to climate change, rainfall events have been predicted to increase in severity in coming decades (Kendon et al., 2014). Since 2009 the majority of the global population has resided in urban areas and this proportion is expected to increase (United Nations, 2010). Sustainable Urban Drainage Systems (SUDS) are increasing in popularity as a solution to many of these problems. Also referred to as Best Management Practices (BMPs), Low-Impact Development (LID), Stormwater Control Measures (SCM), or Water-Sensitive Urban Design (WSUD), the approach seeks to mimic natural drainage regimes using source control, permeable paving, stormwater detention and infiltration, and evapotranspiration (e.g. green roofs) in order to mitigate flooding, improve water quality, and augment the value of recreational amenities and other ecosystem services (Moore and Hunt, 2012; Krasny et al., 2014).

SUDS comprise a variety of different components (Table 1). Each offers a different approach to managing water quality, runoff volume and velocity, and providing amenities and other benefits. The configuration of SUDS components varies between sites and they can be installed in sequence as a "management train" in order to provide benefits incrementally across a catchment (CIRIA, 2007). SUDS offer different costs and benefits than traditional drainage systems. Assessments of ecosystem services (ES) establish a value on all final goods and services provided by ecosystems and consumed by humans (Millennium Ecosystem Assessment, 2005) and represent an increasingly prominent approach to quantifying benefits provided by SUDS and natural systems (Christie et al., 2012). In order to make better informed decisions about drainage solutions, it is best to internalize as many costs and benefits associated with drainage implementation as possible. This approach, called holistic valuation, generally takes into account land take, construction costs, maintenance costs, and ecosystem services (Duffy et al., 2008; Bastien et al., 2010).

Table 1: SUDS Components (after CIRIA, 2007)

SUDS Component	Includes
Source Control	Green roofs, street trees, rainwater harvesting, permeable paving
Swales and Conveyance Channels	Swales, channels, rills
Filtration	Filter strips, filter trenches, bioretention areas
Infiltration	Soakaways, infiltration trenches, infiltration basins, rain gardens
Retention and Detention	Detention basins, retention ponds, geocellular drainage
Wetlands	Inlet zone/sediment basin, macrophyte zone, high flow bypass channel
Inlets, Outlets, and Control Structures	Landscaped pipes, perforated pipes, weirs, orifices, vortex control devices, spillways

Studies comparing whole life costs (WLC) of SUDS to those of equivalent traditional drainage systems (Duffy et al., 2008; Heal et al., 2009) suggest that SUDS are cheaper to maintain than conventional drainage systems (Houle et al., 2013). Sources of recommendations abound for maintenance activities and frequencies at which they should be carried out (CIRIA, 2007; Erickson et al., 2013), but there is a lack of accurate information on the operating and maintenance costs of SUDS (WERF/UKWIR, 2004; Mullaney and Lucke, 2014). Perception among contractors, planners, and engineers about maintenance costs present a barrier to the implementation of SUDS (McKissock et al., 2003), as well as uncertainty as to the multiple benefits they can provide (Narayanan and Pitt, 2006; Moore and Hunt, 2012). This study represents a novel approach to these problems in that it uses field data where possible to assess three ecosystem services provided by SUDS and incorporates those values into WLC methodologies.

Methods

Site Selection

Dunfermline Eastern Expansion (DEX) is a development comprised of residential, retail, industrial, and public recreation land uses located in Fife, central Scotland. To prevent downstream flooding and meet water quality targets, a variety of SUDS features were planned for the 5.9 km^2 site, including ponds, swales, wetlands, and permeable paving. Construction began in 1996 with completion expected by 2020. In comparison to many SUDS features elsewhere, the maturity of those in DEX make the site ideal for studying long term maintenance activities and ecosystem service provision. A study area was selected to include many of the SUDS features currently in place (Figure 1).

GIS Database and SUDS Features Selection

Assembling a geospatially referenced database of SUDS features was necessary to measure their proximity to residences and thereby to analyse the benefits they provide. Geometry data of SUDS features, including ponds, swales, filter drains, permeable paving, and basins, as well as other ponds, watercourses, and residences were generated using EDINA Ordnance Survey annotation tools, satellite imagery, and GPS coordinates gathered in the field. Catchments were digitized according to a previous study undertaken by Spitzer and Jefferies (2007). Where necessary, data on SUDS permanent pool volume, detention volume, and catchment area were later estimated from the GIS database and from other sources. Fifteen SUDS features were selected for analysis (Table 2). Five each of ponds, basins, and swales, were chosen to represent features of varying age, size, and maintenance quality. Filter drains and permeable paving were not selected because they are not included in the WLC methodologies used in this study.

Figure 1: Map of study area showing 15 SUDS features selected for analysis

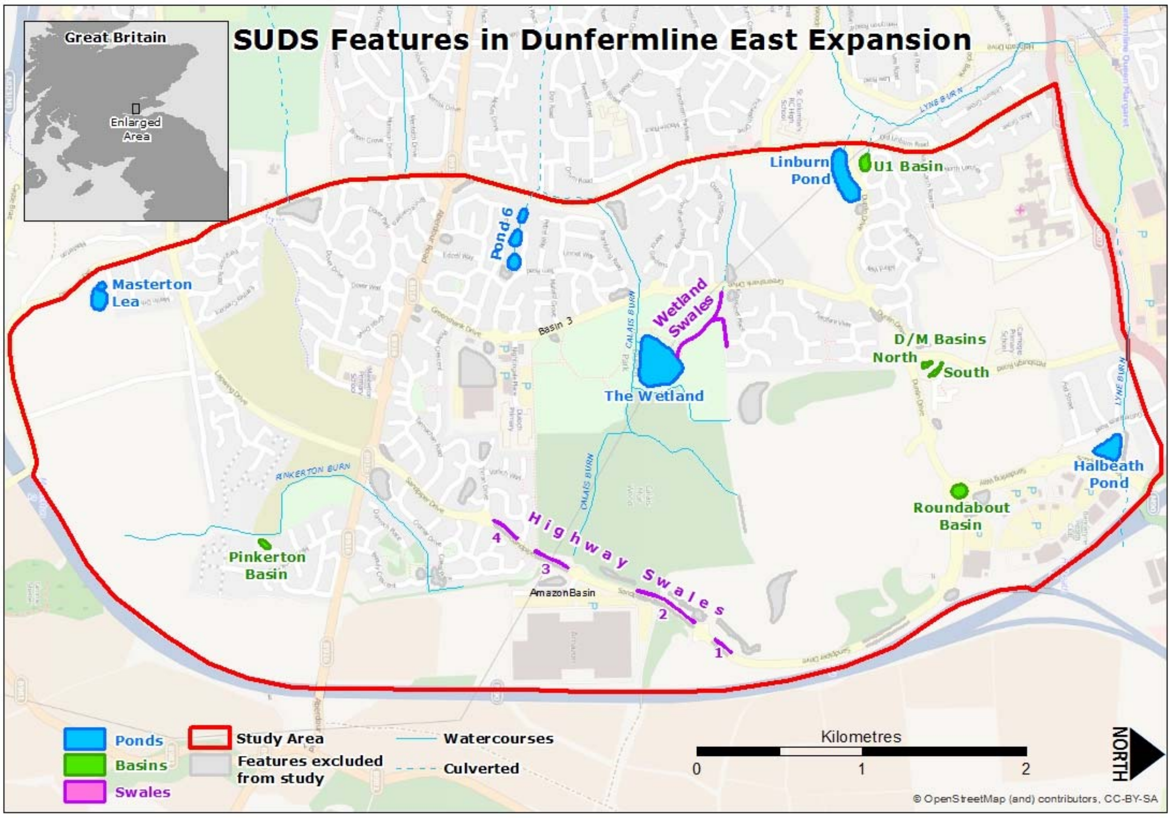


Table 2: SUDS Features selected for study, taken from developer's design specifications and field measurements. Detention volume reflects maximum design capacity.

Feature	Name	Area (m^2)	Detention Volume (m^3)	Factor
Ponds	Halbeath Pond	4,930	18,400	Taylor Wimpey
	Linburn Pond	9,140	61,980	Taylor Wimpey
	The Wetland	18,210	57,300	Local Authority
	Masterton Lea	3,520	21,140	Taylor Wimpey
	Pond 6	4,160	22,604	Developers (x3)
Basins	D/M Basin South	420	332	Developer
	D/M Basin North	510	1,016	Developer
	Pinkerton Basin	680	880	Developer
	U1 Basin	1,420	1,136	Private Factor
	Roundabout Basin	1,840	1,468	Local Authority
Swales	Highway Swale 1	140	1,942	Local Authority
	Highway Swale 2	450	6,272	Local Authority
	Highway Swale 3	250	3,534	Local Authority
	Highway Swale 4	180	2,852	Local Authority
	Wetland Swales	840	11,622	Local Authority

Maintenance Database

SUDS maintenance data were collected to input into WLC methodologies in later analyses. Factors are termed as all organisations responsible for maintenance of SUDS in DEX. They mainly consist of developers or government entities (local authorities). Payment certificates and invoices made available by the developer, Taylor Wimpey, for three of the ponds and the wetland in this study provide details of actual maintenance activities, associated costs, frequencies, and locations where these services were carried out. The payment certificates have been collected by Abertay University's Urban Water Technology Centre (UWTC) since July 1999. This study continued to collect and collate payment certificates up until July 2014.

To obtain maintenance data for the other SUDS used in this study, interviews were conducted in which residents living adjacent to SUDS features were asked which factors were observed performing maintenance activities. Factors were then contacted with requests to share data on maintenance activities and prices. Next, field observations were made to verify maintenance activities had been carried out according to checklists developed by the UWTC for Taylor Wimpey and a private land maintenance factor. Inspections included checking structural features such as embankment stability, fences, signage and inlets (including sediment and water depths), vegetation (amenity, aquatic plants and algae proliferations), and recording water colour and weather conditions.

Ecosystem Services Assessments

Three ecosystem services (ES) provided by SUDS at DEX were evaluated: water quality, hazard management (flooding), and amenity. These particular ES were chosen for assessment based on author consultation with users and other stakeholders interested in quantifying ES benefits. ES values calculated in this section were used later in WLC analysis.

Water quality utilized the estimated value of avoided combined sewer overflows (CSOs). Peak inflows and outflows for Halbeath and Linburn Ponds during events in 2002 were calculated by Spitzer and Jefferies (2007). From these data, mean peak flow reduction was calculated for ponds at DEX to be 12.9% ± 5.2% (95% confidence interval). The Environment Agency (2007) assumes that a 10% reduction in runoff leads to a 90% reduction in CSOs (based on data from the 2007 floods in Hull, UK) and estimates the cost of water quality impairment due to each unsatisfactory CSO at £51,000. Ofwat (2007) estimates a total of 1,000 CSOs per year in England and Wales. This study assumes Scotland experiences an equivalent frequency of CSOs per unit catchment area. Accordingly, the 15 SUDS provide a water quality benefit of £664 annually or as a present value (PV) of £4,552 over a 50-year timespan, discounted at 3.5% (Equation 1).

Equation 1: Formula for calculating present value, PV, (after CIRIA, 2007) where N= time horizon in years, C_t = total monetary costs in year t, and r = discount rate

$$PV = \sum_{t=0}^{t=N} \frac{C_t}{(1+\frac{r}{100})^t}$$

Hazard management was evaluated using weighted annual property damages (WAADS) taken from FHRC (2013) for 5, 10, 25, 50, and 100 year flood events. Because SUDS in DEX were designed to manage 100-year flood events, all WAADS values were included. These values were £9,500, £17,847, £19,716, £23,360, and £26,119 respectively.

Amenity values were based on CNT's assessment that proximity to SUDS increases the value of adjacent residential properties by 3.5% (Center for Neighborhood Technology, 2010). This study identified adjacent properties as lying within a 50 m distance of SUDS features. Using the average house value in Dunfermline of £162,302 (LSL Property Services, 2014) a one-off amenity value of £5,700 per property was calculated.

Whole Life Costs

Whole life costing (WLC) involves identifying all costs in order to build and maintain an asset throughout the course of its useful life, based on standard accounting procedures, particularly present value calculation. A number of WLC decision support tools are available that each offer a different approach (Susdrain). Two WLC methodologies were used in this study: Water Environment Research Foundation (WERF) (2009) and SUDS for Roads – Whole Life Cost and Whole Life Carbon Tool (Scottish SUDS Working Party, 2009). The former methodology is similar to that used by Duffy et al. (2008), allowing for the possibility of comparing results, in order to assess changes in price over time.

SUDS for Roads was chosen because it is among the most recent WLC methodologies developed and it allows users to analyse treatment trains consisting of multiple SUDS features as well as individual SUDS. The same construction costs were used in both WLC methods. Construction costs for four of the ponds and the wetland were available from Duffy (2004). Construction costs of the four highway swales were obtained from the developer. Based on these, the construction costs of the wetland swales were estimated. Data were unavailable for the five detention basins, so construction costs were estimated (Equation 2).

Equation 2: Formula for calculating the construction cost of detention basins (United States Environmental Protection Agency) where C = cost (US$), V = detention volume (ft^3).

$$C = 12.4V^{0.0760}$$

Because the two WLC methodologies used in this study do not include ES values in their calculations, subsequent net present value (NPV) calculations were carried out separately. The results of all monetary calculations are expressed as pounds sterling (£) valued at the times costs were incurred.

WERF BMP and LID Whole Life Cost Models

A total of nine tools are available. Those pertinent to the SUDS features in this study were used, namely: detention basin, retention pond, and swale. WERF's methodology consists of a macros-enabled Microsoft Excel spreadsheet with six tabs. The tool allows users to choose default values or manually enter values for design specifications, construction, maintenance costs, time horizon (which was set at 50 years), and discount rate, which was set at 3.5% following recommendations of HM Treasury (2011). Values were entered for drainage area, impervious cover, watershed land use type, and facility storage volume based on data supplied by factors, field observations, or GIS calculations. Prices and frequencies for a total of 12 maintenance activities were manually entered: inspection, grass cutting, litter picking, weeding, aquatic plant aftercare, algae removal, pruning/trimming, fence/sign erection/repairs, inlet/outlet maintenance, filter drain maintenance, silt removal, and other maintenance. The former six activities were entered as routine maintenance and the latter were entered as corrective/infrequent maintenance.

SUDS for Roads – Whole Life Cost and Whole Life Carbon Tool

SUDS for Roads, developed by the Scottish SUDS Working Party, consists of a macros-enabled Microsoft Excel spreadsheet. Similar to the WERF costing tool, the same data as for WERF were entered for design specifications, construction costs. The same time horizon and discount rate were entered, which were 50 years and 3.5% respectively. The SUDS for Roads tool is locked down and does not allow users to introduce new maintenance activities, so in this study, the six routine maintenance activities (identified above) were entered, and corrective/infrequent maintenance activities were averaged into two categories. The first included pruning, trimming, fence/sign erection/maintenance, and the second included inlet/outlet maintenance, filter drain maintenance, silt removal, and other maintenance. The SUDS for Roads methodology allows users to analyse SUDS features as stormwater treatment trains containing up to three components. Although many of the SUDS in DEX belong to such treatment trains, 14 of the features in this study were analysed individually in order to enable comparison with the WERF model results. Pond 6 was analysed as a treatment train in order to reflect the fact that it consists of three separate ponds

Results and Discussion

Ecosystem Services Assessments

Water quality and hazard management values seem low in comparison to similar SUDS installations (Aecom & Severn Trent Water, 2013). FHRC's assumptions about precipitation patterns and property values are implicit in the estimates and have been calibrated for the UK. The applicability of this methodology elsewhere would need to be verified. Given climate change, what was previously regarded as a 100-year precipitation event may occur more frequently. Hence, these assessments could underestimate water quality value and may need to be revised in the future.

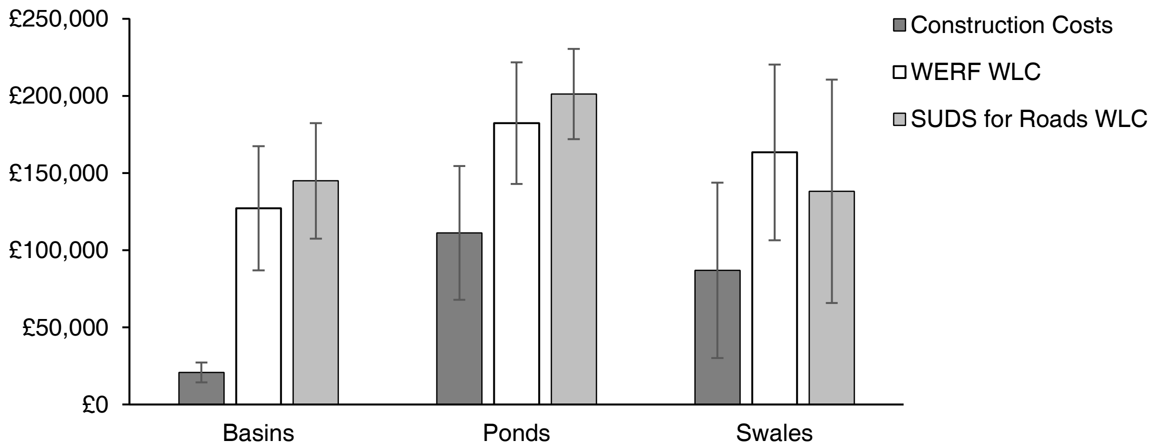
Whole Life Costs

The two WLC methodologies used in this study produced different results (Table 3) that varied by £37,086 ± £27,810 (mean ± 1 standard deviation, n = 15). Because the same construction cost values were used in both methodologies, the differences in WLC cost estimates between the two models is likely due to the assumptions about maintenance cost and activities that are built into the SUDS for Roads tool and are not changeable by users. SUDS for Roads calculates maintenance costs based on the area of the unit serviced whereas WERF allows users to enter maintenance costs per visit. Of the three SUDS features studied, ponds had the highest WLC and detention basins the lowest WLC (Figure 2). The main reason for the differences in WLCs between SUDS feature types is the variation in construction cost since maintenance activities varied little between SUDS features types.

Table 3: Differences in WLCs of selected SUDS at DEX 2014 calculated using two different WLC methodologies. The same values for construction costs were used in both WLC methods.

Site	Construction cost	WERF WLC	SUDS for Roads WLC	Difference
Halbeath Pond	£101,193	£203,016	£167,584	-17%
Linburn Pond	£174,388	£222,853	£248,031	11%
The Wetland	£65,847	£146,289	£215,323	47%
Masterton Lea	£64,808	£123,005	£224,456	82%
Pond 6	£149,951	£216,631	£234,955	8%
DM Basin S	£9,397	£106,824	£117,242	10%
DM Basin N	£21,986	£140,002	£110,613	-21%
Pinkerton Basin	£19,711	£79,575	£113,889	43%
U1 Basin	£23,933	£199,654	£186,969	-6%
Roundabout Basin	£29,082	£109,502	£195,805	79%
Highway Swale 1	£32,188	£108,669	£68,752	-37%
Highway Swale 2	£103,918	£180,399	£159,027	-12%
Highway Swale 3	£58,549	£135,030	£102,329	-24%
Highway Swale 4	£47,265	£123,746	£87,955	-29%
Wetland Swales	£192,574	£269,055	£273,037	1%

Figure 2: Comparison of mean WLC and construction costs by SUDS feature type (n=5, error bars represent 95% confidence intervals).



Estimating Ecosystem Services Effect on Net Present Value

Neither of the two WLC methodologies used in this study accounted for ES provided by SUDS. To evaluate the impact of ES on net present value (NPV), WLC was subtracted from total ES values (Table 4). Including ES did not completely offset the WLC for most SUDS sites, but reduced WLC by about a third for both WLC methodologies at 35 ± 37% and 33 ± 39% (mean ± 1 standard deviation, n = 15) for the WERF and SUDS for Roads methodologies, respectively. Pond 6 yielded a positive

NPV, meaning the value of the ES it provides are greater than that of its construction and maintenance costs. The same was true of Highway Swale 4 using the SUDS for Roads WLC method. Both of these features lie within close proximity to a number of residences, which resulted in high amenity values.

Table 4: Net present value (NPV) of 15 SUDS sites calculated by subtracting ecosystem services values (water quality, hazard management and amenity) from WLC calculated by two different methodologies.

Site	Water quality	Hazard Management	Amenity	NPV WERF	NPV SUDS for Roads
Halbeath Pond	£394	£21,954	£0	-£180,668	-£145,237
Linburn Pond	£19	£73,950	£5,700	-£143,184	-£168,362
The Wetland	£484	£68,367	£0	-£77,438	-£146,472
Masterton Lea	£249	£25,223	£17,100	-£80,433	-£181,884
Pond 6	£1,228	£26,970	£222,300	£33,866	£15,543
DM Basin S	£42	£396	£0	-£106,386	-£116,805
DM Basin N	£134	£1,212	£0	-£138,655	-£109,266
Pinkerton Basin	£76	£1,050	£68,400	-£10,049	-£44,363
U1 Basin	£61	£1,355	£51,300	-£146,938	-£134,252
Roundabout Basin	£453	£1,752	£0	-£107,297	-£193,601
Highway Swale 1	£1,328	£2,318	£0	-£105,024	-£65,107
Highway Swale 2	£7	£7,483	£0	-£172,909	-£151,537
Highway Swale 3	£22	£4,216	£22,800	-£107,992	-£75,291
Highway Swale 4	£24	£3,403	£114,000	-£6,318	£29,473
Wetland Swales	£31	£13,867	£85,500	-£169,657	-£173,639

Uncertainties in the Ecosystem Services Assessments and WLC Estimates

A variety of studies have assessed ES provided by SUDS or similar systems, but the findings have largely been qualitative (Moore and Hunt, 2012; Marlow et al., 2013). No published studies have assessed ES of SUDS in the UK in a quantitative manner (Lundy and Wade, 2011).

WLC estimates for SUDS previously studied by Duffy et al. (2008) and in this study are both substantially lower compared to the installation of traditional drainage systems at the same sites (Table 5). The SUDS WLC estimates reported by Duffy et al. (2008) were greater than in this study, which was likely due to the use of a 60-year time horizon and discount rate of 6%, whereas this study used a time horizon of 50 years and a 3.5% discount rate as recommended by HM Treasury (2011).

Locations of residences, although taken from EDINA Ordnance Survey's most recently published data, may not have accurately reflected the residential properties that had been completed and occupied by the time this study was undertaken. This may have caused amenity to be undervalued.

Table 5: Comparison of WLCs of traditional drainage systems and of selected SUDS sites calculated using the WERF/UKWIR WLC method (Duffy et al., 2008) and the WERF WLC method in this study. Difference is shown between Duffy 2008 WERF/UKWIR calculations and those of this study.

	Duffy et al. 2008		This study	Difference
SUDS Site	WLC Traditional	WLC WERF/UKWIR	WLC WERF	
Linburn Pond	£1,488,227	£394,291	£222,853	-43%
Pond 6	£408,307	£275,449	£216,631	-21%
Halbeath Pond	£339,185	£290,092	£203,016	-30%
The Wetland	£1,288,238	£181,065	£146,289	-19%

The two WLC methodologies used in this study assessed operating and maintenance costs of SUDS, but did not take into account impaired functionality due to insufficient maintenance. At SUDS sites where data were gathered from field observations, grass mowing and litter picking were largely the only maintenance activities observed. Excessive sediment accumulation in inlets and outlets was commonly observed, which may have impaired functionality, thereby reducing the value of services provided by the SUDS feature as reported by Hunt et al. (2011). Although the cost savings from the avoided maintenance activities were included in the WERF method which allowed input of actual maintenance cost data, the method did not account for a possible reduction in ES values.

The SUDS for Roads tools asks if operation and maintenance costs begin in the same year construction begins, whereas the WERF tool assumes the useful life of the SUDS begins when construction reaches completion. Due to the greater timespan during which the SUDS incur maintenance, the former tool may result in overestimates of WLCs. In addition, in the SUDS for Roads tool there are only two options for inlets and outlets, concrete headwall or bagwork. However many of the SUDS at DEX have submerged outlets, whose associated maintenance requirements may have been underestimated by the methods used in this study.

Recently, investigation into the benefits provided by SUDS has been of particular interest to urban planners and policy makers (Wise et al., 2010; CIRIA, 2013). The approach used in this study was novel through: (i) the incorporation of maintenance costs quantified on site as far as possible into WLC estimates and (ii) quantification of ES provided by SUDS. Evidence suggests SUDS provide a variety of ES beyond those assessed in this study (CIRIA, 2013), but so far no robust methodologies exist for investigating them. This study only pertains to ponds, basins and swales. The extent to which other SUDS components provide benefits and the structure of their maintenance costs throughout their useful lives remains to be evaluated.

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