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Rapid assessment of the cost-effectiveness of low impact development for CSO control

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Abstract

This paper presents a simple model for assessing the cost-effectiveness of investments in low impact development (LID) for reducing combined sewer overflows (CSOs) in urban watersheds. LID systems, including green roofs, porous pavement, and stormwater treatment wetlands, are site-specific controls for stormwater runoff. If applied throughout a watershed, LID systems like these can reduce the amount of runoff entering the sewer system and reduce CSOs. To be conservative, we focus solely on the function of LID systems as stormwater management techniques, neglecting the other environmental benefits commonly associated with these technologies. A model is presented that can be used to simulate the cost-effectiveness of reducing CSOs through incremental installation of LID technologies across urban watersheds, when they are introduced alone, or in combination with conventional CSO abatement technologies. The potential reduction in CSOs resulting from various levels of LID adoption is simulated using a modified Rational Method. A life-cycle cost analysis is used to compare LID with other alternatives. Given that LID implementation on private property leads to reduced CSOs, a cost sharing scheme is presented that divides the total LID cost into a private cost fraction (born by the property owner) and a public cost fraction (provided by a public agency). The implications of such a policy are discussed with reference to a CSO-shed that drains to the Gowanus Canal (Brooklyn, NY). The results indicate that individual LID systems have differing levels of cost-effectiveness in terms of CSO reduction, but that under a variety of performance and cost scenarios a public subsidy to encourage LID installation represents a cost-effective alternative for public agencies to consider in their efforts to reduce CSOs. Future areas of research in this field are outlined.
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1. Introduction

Traditional stormwater management (SWM) involves the efficient capture, conveyance, and treatment of rainfall-induced runoff generated on impervious surfaces. Many urban areas utilize combined sewers to convey household sewage and stormwater runoff to water pollution control facilities (WPCFs) for treatment. Combined sewers are designed to convey sewage and a limited amount of stormwater runoff. When runoff exceeds available system capacity, combined sewer overflows (CSOs) occur as direct discharges to water bodies.

CSOs are relatively common because they can be caused by even small (i.e. <30 mm) storms (Novotny and Olem, 1994). Nationally, CSOs are a leading cause of pollution in rivers, lakes, and estuaries and the United States Environmental Protection Agency (USEPA) estimates the cost of CSO abatement at over US$ 44 billion (USEPA, 2002). Currently, 828 nationally permitted combined sewer systems release approximately

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3.2 million m^3 of untreated sewage to surface water bodies from approximately 9300 CSO discharge points to surface water bodies each year (USEPA, 2004).

The quantitative importance of CSOs has not received a lot of attention in the literature (Evan et al., 2004; Buerge et al., 2006). Recent studies highlight the extent of potential impacts to receiving bodies, which vary temporally with antecedent weather conditions, and spatially as a function of differences in land use, population density, traffic intensity as well as urban planning and drainage policies between catchments (Butler and Davies, 2004; Suarez and Pertas, 2005). The concentrations of suspended solids and particulate phase organic pollutants in effluent from one of Boston's largest CSOs approach those of untreated sewage, and the influence of the CSO on local water quality is evidenced by similarities between the organic chemical composition of the CSO effluent and those in the receiving waters (Eganhouse and Sherbolm, 2001). Iannuzzi et al. (1997) identified CSOs as the link between chemicals used by industries operating in the CSO districts and the degraded sediment and water quality in the lower Passaic River in New Jersey. Suarez and Pertas (2005) report event mean concentrations of COD, BOD5, and SS as 587 mg/l (S.D. = 212), 316 mg/l (S.D. = 104), and 512 mg/l (S.D. = 193), respectively considering multiple storms in five Spanish cities. Using an electron microscope to investigate the nature of trace element carriers, El Samrani et al. (2004) found various mineral forms of alloys and metals, iron oxyhydroxides, carbonates, phosphates, sulfides, sulfates, and clays in CSO samples collected in Nancy, France.

To avoid these impacts, conventional approaches to CSO abatement generally seek to increase storage or conveyance capacity within the sewer system. Two common designs are in-line storage systems and CSO tanks. In-line storage systems add storage volume within the sewer system, while CSO tanks are large underground chambers situated at CSO discharge points. Both systems avert discharges by storing and in some cases also treating excess sewer flow before releasing it slowly back to the sewer system. These approaches can be effective but are often expensive and difficult to site, especially in urban areas where the availability of land is limited and land acquisition costs can be relatively high.

Low impact development (LID) is a relatively new approach to SWM, more commonly implemented in new and suburban developments (Hager, 2003; Ferguson, 2002; Prince George's County, 1999). LID can be defined as a land development and retrofit strategy that emphasizes the protection and use of distributed interventions to reduce the volume and rate of stormwater runoff from a developed landscape. It is achieved through the adoption of site and infrastructure designs that sustain, or attempt to replicate pre-development site hydrology in the post-development condition. LID systems include redirected roof leaders, stormwater infiltration systems, rain gardens, stormwater wetlands, rainwater harvesting and reuse systems, and rooftop detention systems, distributed throughout the landscape (USEPA, 2000).

Although some municipalities such as Portland, OR, Milwaukee, WI, Seattle, WA, Philadelphia, PA are exploring various incentives and subsidies of LID installations (Tilmans, 2007), to date, LID has not been widely implemented in highly urbanized areas. This is in part because of a perception that insufficient land is available for LID implementation in cities, and also because of a belief that LID is costly to retrofit or introduce into urban landscapes. In reality, LID systems are most effective when applied on private land, which, in urban areas, occupies a large fraction of the landscape. For example, 40% of New York City's urban runoff originates on private roofs and driveways (Heaney et al., 1999). Efforts to reduce urban runoff from private property can be very successful as evidenced by, for example, Portland's Downspout Disconnect Program. Introduced in 1993, the program began offering residents of selected neighborhoods a US$ 53 incentive to redirect roof runoff to gardens and lawns. As of 2005, more than 47,000 homeowners have disconnected, removing about 4.2 million m^3 of stormwater per year from the combined sewer system (Portland 2006).

USEPA research indicates that while the installation costs of LID technologies are generally more expensive than conventional stormwater infrastructure, they can be more cost-effective on a volumetric basis for storing stormwater in the landscape (Table 1). However, the means by which the costs and benefits for SWM are usually distributed underscores one major obstacle to widespread LID adoption. While public agencies stand to benefit from LID installations in a particular watershed, in general those agencies do not pay for LID interventions made on private property. Private property owners may marginally benefit from onsite LID in terms of increased real estate value, reduced chance for flooding, etc., but usually bear the brunt of LID installation and maintenance costs. In this context, an

Table 1
Comparison of unit installation and stormwater storage costs for LID and conventional alternatives

Type of land surface	Design type	Installation cost per unit (US$ 1999)	Storage cost (US$/liter)
Parking areas	Conventional	0.23	2.43
	LID (porous pavement)	0.25	0.16
Sidewalks	Conventional	0.19	1.96
	LID (porous concrete)	0.19	0.16
Streets	Conventional	0.25	2.58
	LID (porous pavement)	0.26	0.22
Storage	1 million gal CSO tank	NA	1.20
	Infiltration/detention basins	5.00	0.26

Calculations are for a hypothetical site with soil type B (Heaney et al., 2002).

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exploration of the use of public policies, incentives, and subsidies to promote LID installation on private property appears worthwhile. Moreover, where land acquisition, siting issues and hard infrastructure costs limit the use of conventional SWM techniques, LID offers public agencies a SWM alternative that appears worthy of additional consideration.

This paper presents a simple model for performing a low impact development rapid assessment (LIDRA) that can be used to measure the cost-effectiveness of distributed implementation of various forms of LID as a means of achieving CSO abatement in urban areas. The LIDRA model can be used as a policy-planning tool to compare LID introduced alone or in conjunction with traditional SWM techniques, to conventional approaches focusing wholly on centralized infrastructure. A case study is presented employing LIDRA to compare CSO reductions achievable through public subsidies promoting porous pavement, green roofs, and a treatment wetland to those expected from construction of a CSO tank, in Brooklyn, NY. Initial simulations use a range of runoff reduction performance and cost estimates as an illustration. A sensitivity analysis provides a basis for concluding that LID systems may offer SWM managers a viable alternative to centralized approaches for reducing CSOs. Ongoing areas of research are outlined.

2. Summary of the LIDRA method

LIDRA assesses cost-effectiveness using hydrological and cost accounting methods applied to specific LID systems that can be incrementally installed across a landscape. This section summarizes the main elements of this method.

2.1. Hydrologic effectiveness

The hydrologic component of LIDRA represents LID effectiveness in terms of an estimated change in annual CSO hours resulting from LID installation. A CSO hour is defined as an hour during which a CSO event occurs, and is enumerated using the modified Rational Method, as described in the following.

LID technologies, distributed spatially within urban watersheds, can mimic a spectrum of natural landscape hydrologic processes by routing rainwater through complex flow pathways. Hydrologic and hydraulic (H&H) modeling of such processes using rainfall–runoff models would require high resolution definition of subcatchments and sewer branches, not practical at the scale of a typical urban sewershed because of higher model setup costs, run times, and difficulties in model convergence. To overcome this problem, LIDRA uses a simple, three-step method to estimate how changes in landscape imperviousness as a result of LID implementation would alter the number of CSO discharge hours that would occur from a given CSO-shed. These three steps are:

(1) Identify the quantity of rainfall that causes CSO discharge from a given CSO-shed.
(2) Represent CSO-causing rainfall intensities as a series of threshold peak runoff flow rates from the CSO-shed using a modified form of the Rational Method.
(3) Using the fixed threshold peak runoff flow rates, modify the imperviousness of the drainage area, quantifying corresponding changes in the amount of rainfall required to trigger a CSO.

Key assumptions implicit in this conceptual model are that threshold peak runoff flow rates correlate well with the threshold sewer flows that actually cause CSOs, and that CSOs occur at random with respect to the diurnally fluctuating flow of wastewater and tidal inflow to CSO outfalls.

Data requirements for LIDRA include the existing level of imperviousness in the pre-LID watershed, an hourly precipitation record and the corresponding time of onset of each CSO event that occurred during that time series. The time of CSO onset can be obtained through observation, remote monitoring, or low resolution H&H modeling of the landscape and sewer system. (This data is often available because characterization, monitoring, and modeling of the combined sewer system and receiving waterbody are one of the nine elements of a CSO long-term control plan required of sewer district managers by Federal policy.) The quantity of precipitation causing CSO events is obtained by cross-referencing the precipitation time series with the time of onset of each CSO event during the study period. In this way, a series of CSO-causing rainfall intensities are estimated for the study area.

The Rational Method, a well known approach used to estimate peak runoff flow rates from small urban watersheds, provides the central relationship for relating data on watershed imperviousness, rainfall, and CSO events. The method is used to represent each CSO-causing rainfall event as a threshold peak runoff flow rate. The rainfall intensity term is expressed as the cumulative depth of rainfall preceding the onset of a CSO event divided by the duration of that rainfall, as shown in the following:

$$Q_t = C_{\mathrm{ex}} i A = C_{\mathrm{ex}} \frac{d_{t,C_{\mathrm{ex}}}}{t} A \tag{1}$$

where Q_t is the peak runoff flow rate caused by rainfall of duration t and depth $d_{t,C_{\mathrm{ex}}}$ ($\mathrm{m^3/s}$); C_{ex} is the dimensionless runoff coefficient corresponding to the existing level of imperviousness in the CSO-shed; $d_{t,C_{\mathrm{ex}}}$ is the cumulative depth of rainfall preceding a CSO; t is the duration of rainfall preceding a CSO; i is the rainfall intensity, represented as $d_{t,C_{\mathrm{ex}}}/t$ (mm/h), and A is the total watershed area (ha).

The runoff coefficient is a simple means of empirically representing surface types and other hydrologic abstractions in the Rational Method. Although runoff coefficients are by definition simplifications of hydrologic performance, they continue to be used extensively by regulators to evaluate proposed drainage plans. Higher C values are associated with higher levels of imperviousness. Typical C values for lawns, parks, and playgrounds range from 0.10 to 0.40 and depend on soil conditions. Impervious surfaces such as roofs, streets, driveways, and sidewalks range from 0.70 to 0.95. Composite C values are calculated for watersheds with different types of surfaces using an area-weighted average.

Eq. (1) is used to calculate Q_t values for the rainfall preceding onset of a CSO during a particular study period. Each Q_t

value defines an effective threshold peak runoff flow rate that, when exceeded, caused a CSO in the CSO-shed under existing conditions. These Q_t values are used as markers indicating specific patterns of antecedent rainfall that trigger a CSO, given the existing configuration of the sewer system and drainage area.

Next, to determine how implementation of LID could change the frequency of CSO discharge events, Eq. (1) is rearranged and substitutions made as per below:

$$d_{t,C_p} = \frac{Q_t t}{AC_p} \tag{2}$$

where C_p is the composite runoff coefficient corresponding to a potential level of LID implementation in the sewershed, and d_{t,C_p} is the depth of rainfall falling over time, t, that would result in CSO discharge in the modified watershed. Note that C_p is the weighted average that considers replacement of a particular set of surfaces within the sewershed with LID alternatives.

The values of d_{t,C_p} are indexed by both storm duration, t, and varying levels of landscape imperviousness, represented by different C_p values. Eq. (3) represents d_{t,C_p} as a function of C_p:

$$d_{t,C_p} = \frac{C_{ex}}{C_p} d_{t,C_{ex}} \tag{3}$$

The last step of the hydrological method involves querying the rainfall record to determine the reduction in annual CSO hours (as a percentage of existing conditions) for different levels of LID installation (e.g. different C_p values).

2.2. Measures of LID Costs and benefits

For reference, typical installation and O&M costs for LID installations found in the literature, adjusted to 2006 dollars, are shown in Table 2. Actual costs vary from location to location and with various economic factors.

In order to analyze how LID might be integrated into a public SWM program, it is important to differentiate between public (i.e. government) and private costs and benefits. Public costs include governmental expenditures, and public benefits relate to a reduction of CSOs, which is also a reduction in public liability. Private costs for LID are those borne by individuals who install systems on their property. Private benefits may include the basic function of the systems as a driveway, sidewalk, or roof surface as well as potential life-cycle cost savings, energy cost savings (of green roofs), water cost savings (of rainwater harvesting), and aesthetic value.

LIDRA tests the argument that because of the potential public benefits of widespread adoption and retrofitting of LID into urban watersheds, it might be cost effective for public sewer agencies to share the cost of LID with private property owners. LIDRA accomplishes this by separating estimates of the total cost of LID into public and private cost components. The private cost component is set at the cost of a conventional surface. That property owners would not be willing to pay a premium for LID is implicit in this assumption. The public cost component of LID, to be sourced from public SWM/CSO control budgets, is defined as the difference between the total cost of an LID option and its conventional alternative, on a life-cycle basis. Life-cycle analysis (LCA) is necessary because the systems differ with respect to durability, initial costs, and annual operations and maintenance costs. As such, the public subsidy considered would make up the cost difference ordinarily witnessed by property owners when faced with the choice to build a conventional or LID surface.

2.3. Cost-effectiveness of LID

LIDRA links the public expenditures to promote LID with the effectiveness of LID technologies for reducing CSOs, to arrive at the cost-effectiveness of LID implementation as a CSO reduction strategy. After obtaining functional relationships between (a) C_p and the public subsidy amount required to make integration of LID technologies cost neutral to property owners and (b) C_p and percent reduction in CSOs, it is possible to determine cost-effectiveness curves for CSO reduction through a government program to promote LID, which can be compared to cost-effectiveness curves developed for CSO storage tanks, or any other alternative approach to CSO control.

3. LIDRA case study: Gowanus Canal

This section describes an application of LIDRA to a CSO-shed in Brooklyn, NYC. New York City is an appropriate site for

Table 2
LID installation and O&M costs from a variety of sources in 2006 dollars

LID technology	Installation cost (US$ 2006)	O&M costs	Source
Rain gardens	US$ 107–129 m^{-2} (US$ 13–15 ft^{-2})		Bannerman (2003)
Stormwater planters	US$ 426 m^{-2} (US$ 39.60 ft^{-2})	2–8% of installation cost	PBES (2006b), Flinker (2005)
Porous concrete	US$ 28–90 m^{-2} (US$ 2.50–8.30 ft^{-2})	1–2% of installation cost	USEPA (1999a), CRI (2005), NCGBT (2003)
Grass/gravel pavers	US$ 22–86 m^{-2} (US$ 2.10–8.00 ft^{-2})	1–2% of installation cost	USEPA (1999a)
Interlocking concrete paving blocks	US$ 75–150 m^{-2} (US$ 7.00–13.90 ft^{-2})	1–2% of installation cost	USEPA (1999a)
Porous asphalt	US$ 67–85 m^{-2} (US$ 6.30–7.90 ft^{-2})	Not available	PADEP (2005)
New green roofs	US$ 69–165 m^{-2} (US$ 6.40–15.30 ft^{-2})	10–16% of installation cost	Peck and Kuhn (2003)
Retrofit green roofs	US$ 95–276 m^{-2} (US$ 9.00–25.50 ft^{-2})	6–11% of installation cost	Peck and Kuhn (2003)
Cisterns	US$ 0.14–1.17 l^{-1} (US$ 0.50–4.00 gal^{-1})	Not available	TWDB (2005)
Constructed treatment wetlands	US$ 14,200–60,700 ha^{-1} (US$ 35,000–150,000 $acre^{-1}$)	Low	BNL (2007)
Stormwater wetland	US$ 26,100–36,200 ha^{-1} (US$ 64,700–89,200 $acre^{-1}$)	2–4% of installation cost	SFBF (2001)

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Fig. 1. The OH-007 drainage area, discharging into the Gowanus Canal (Brooklyn, NY).

this study because combined sewers serve 80% of the City, with over 450 discharge points. CSOs are the largest single source of pathogens in the New York Harbor and the NYCDEP is currently under Consent Order to spend hundreds of millions of dollars in the next 10 years on CSO abatement (NYCIBO, 2004; NYCDEP, 2002).

3.1. Site description

Overflows from the case study CSO-shed are discharged into the Gowanus Canal, a tidal tributary to the New York Harbor in Brooklyn, NY (Fig. 1). The Gowanus Canal was constructed during the nineteenth century on the site of a former saltmarsh and creek to accommodate the growing industrial, commercial, and maritime activities on the Brooklyn waterfront. The canal watershed is over 700 ha and is almost entirely urbanized with 55% of its land in residential use, much of which consists of residential row houses. The majority (92%) of the watershed is drained by combined sewers. Ten CSO discharge points line the Canal, annually discharging over 1.1 million m^3 of combined sewage (NYCDEP, 2004), and are one reason that the Gowanus Canal is listed on the 2004 New York State Section 303(d) list of impaired waterbodies and has been designated as a Track I CSO planning waterbody by the New York City Department of Environmental Protection (NYCDEP).

The drainage area associated with a single CSO outfall (OH-007) was selected for this case study. GIS analysis of aerial photographs was used to disaggregate the surfaces present in the 141 ha CSO-shed. In total, 85% of the CSO-shed is impervious and drains into a combined sewer system that annually discharges 260,000 m^3 (approximately 25% of the total annual volume released into the canal) during about 50 different events (NYCDEP, 2004). Table 3 shows the types of land surfaces present; the percent of the total CSO-shed area that they represent; and the applicable LID system considered for that surface.

Table 3
Existing land use in the OH-007 sewer-shed

Land cover type	Percent of land area	LID application
Roofs	47	Green roof
Sidewalks	14	Porous concrete
Driveways and parking lots	6	Porous asphalt
Streets	18	Curbside channels
Lawns	15	None

3.2. Conventional CSO abatement

The NYCDEP has developed cost-effectiveness curves for CSO tanks of various sizes fitted to OH-007 (Hydroqual, 2004/2006). The construction cost for CSO tanks of different sizes are listed in Table 4. The data indicates, for example, that a CSO tank costing approximately US$ 25 million to construct could reduce CSOs by about 25%. Although USEPA research

Table 4
Cost-effectiveness of CSO tanks (Hydroqual 2004/2006)

Tank size	Cost (million US$)	%Reduction in CSO	Cost-effectiveness (million US$/%reduction)
Small	25	25	1
Medium	45	35	1.3
Large	65	40	1.6

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(1993) indicates that CSO tank costs in general decline with increasing volume, this data indicates decreasing returns with scale in terms of the percent reduction in CSOs achieved. That is, the largest reduction per level of expenditure is accomplished with the smallest tank. Although it is unclear precisely why this is the case, the diminishing returns associated with larger tanks could be due to specific infrastructure issues associated with the configuration of sewer pipes or to property acquisition costs, which, as has been stated earlier, are not reflected in these cost figures.

3.3. Analysis of LID in Gowanus Canal

3.3.1. LID application

Three LID systems are examined in this study: green roofs, porous pavement, and a treatment wetland. These technologies and their specific applicability to this case study are described individually below.

3.3.1.1. Green roofs. Green roofs, also known as eco-roofs, are vegetated roof coverings that retain and detain stormwater, insulate buildings (lowering building energy demand), buffer noise, and create new urban habitats. With respect to SWM, green roofs reduce peak discharge flow rates, and detain and retain precipitation. Many different green roof designs are currently available, and numerous studies have documented the reduction of runoff from green roofs. Reviews of this work have been compiled by Dunnett and Kingsbury (2004), and by Mentens et al. (2006), who specifically derived empirical annual and seasonal rainfall–runoff relationships for these systems from an analysis of 628 sets of green roof measurements extracted from eighteen publications. In particular, these authors report that annual runoff from green roofs is significantly correlated to annual precipitation, type of roof, number of layers, and depth of substrate, while no significant correlation is found with roof age, slope angle, and length. VanWoert et al. (2005) measured the effects of roof surface, slope, and media depth on green roof stormwater retention rates, and reports that a combination of reduced slope and deeper media clearly reduced the total quantity of runoff. Vegetation was found to increase stormwater retention, but the effect was minimal relative to the influence of the growing media. Bengtsson (2005) derived intensity–duration–frequency relationships for a thin, extensive green roof in Sweden, from which he concludes that the probability of high runoff from thin green roofs is much lower than from hard roofs. Bengtsson et al. (2005) found that annual runoff from a 3 cm sedum-moss roof in southern Sweden is about half of the precipitation, corresponding to runoff from small agricultural basins, and also that runoff occurs only after field capacity has been reached.

Runoff coefficients of between 0.7 and 0.1 have been proposed for green roofs with depths ranging from 20 to >500 mm (DeCuyper et al., 2005). Under laboratory-simulated NYC five-year storm conditions, we have computed runoff coefficients of 0.21, 0.39, and 0.53 for green roof test plots of 2.5, 6.25, and 10 cm substrate depths (Montalto et al., 2007a).

Most buildings in the case study CSO-shed have flat roofs. A structural assessment on a brownstone in the OH-007 watershed concluded that, with minor structural modifications, typical buildings in the study area could support an extensive green roof with 10–13 cm substrate depths, the green roof construction type assumed in this analysis. It was assumed that up to 90% of all row houses within the study area could support such a roof.

3.3.1.2. Porous pavement. Porous pavements (such as porous concrete and porous asphalt) are gaining acceptance and application flexibility as construction materials for sidewalks and parking lots (Ferguson, 2005; USEPA, 1999a,b). These systems facilitate the storage and infiltration of precipitation into the soil or other subsurface storage volumes, reducing peak discharge rates and creating less runoff. Porous pavements are best applied where vehicle traffic is minimal and access for cleaning and maintenance is possible. Other constraints associated with porous pavement include subsurface soil types, depths, and permeability, although both infiltration and exfiltration porous pavement systems can be constructed.

Runoff coefficients for porous asphalt and porous concrete have been estimated at 0.12–0.4, newly installed, and 0.18–0.29, three to four years after installation (Ferguson, 2005). USEPA research recognizing porous pavements as a cost-effective approach to reducing CSOs and improving urban water quality dates back to the 1970s (Field et al., 1982). Reduced outflow volumes from monitoring of hydrologic performance of four UK porous paver installations over the course of 62 precipitation events have been used to develop hydrologic relationships between rainfall, outflow, outflow duration, and antecedent conditions (Pratt et al., 1995). Experimental research has focused on quantifying the performance of specific porous pavement installations. Watanabe (1995) reported that permeable pavement and infiltration pipes were responsible for a 15–20% reduction in peak rates of runoff from a 16.7 ha urban study area in Japan. In an experiment designed to compare runoff from four different permeable paver parking stalls to a standard asphalt one, Booth and Leavitt (1999) report that, in response to a 16 h storm that reached a maximum rain intensity of 4 mm/h, the paver systems produced virtually no runoff while peak rates of discharge from the standard pavement varied from 0.5 to 1.1 mm per 15 min. After six years of daily usage, the permeable pavements continued to perform well, producing virtually no runoff during 15 distinct precipitation events occurring over five months and totaling 570 mm of precipitation with a maximum intensity of 7.4 mm/h (Brattebo and Booth, 2003). In a set of experiments in Athens, Georgia, a porous parking lot built over low permeability clay-rich soils was found to produce 93% less runoff than a standard asphalt lot, as measured during nine different storms totaling between 0.03 and 1.85 cm of rainfall each—the most common type of storms experienced in that region (Dreelin et al., 2006). Although less than 4% of all rain events caused discharge from its underground reservoir, the concentrations of metals (Pb, Cu, Cd, and Zn) and suspended solids measured in water quality samples pulled from the reservoir structure outlet of a French porous asphalt installation were significantly lower than those measured at the outlet of a reference conventional pavement. Samples taken from the pavement's reservoir structure and the soil underlying it after four and eight years of operation indicated

that metallic pollutants were retained in the porous asphalt layer, with no contamination of underlying soils (Legret et al., 1996; Legret and Colandini, 1999).

Inspection of a soil boring taken within the study CSO-shed and consultation with local landscape historians indicated the likely presence of soils suitable for porous pavements in the CSO-shed. The soils in the upper portions of the CSO-shed consist of typical terminal moraine found in this portion of New York State. Soils in the lower portions of the CSO-shed consist of fill materials including the fly ash used to fill in the Gowanus wetlands, and spoil material excavated during building construction elsewhere in the CSO-shed. The analysis considered the replacement of sidewalks and parking surfaces within OH-007 CSO-shed with porous pavement, constructed with an underground porous media reservoir sized large enough to store the two year storm volume generated over the pavement's catchment area. A perforated overflow pipe would direct excess flows to storm sewers, to avoid pavement surface flooding. Because the peak flow rate and quantity of runoff from porous pavement designed this way are both less than from conventional parking lot and sidewalk surfaces, the runoff coefficient of the porous pavement surfaces is reduced.

3.3.1.3. Stormwater treatment wetland scheme. The third LID approach considered involves the conveyance of rainwater harvested from street surfaces to a specially designed treatment wetland, located within the CSO-shed. The city of Zurich, Switzerland has successfully implemented such a system as a means of averting CSO discharges caused by stormwater runoff from rocky escarpments that surround the city (Conradin, 1995). A number of projects in both Portland (PBES, 2006b), and Seattle (SPU, 2006), also make use of landscaped curb extensions, curbside infiltration swales, and other street edge alternatives to direct street runoff away from combined sewer systems.

Over the past 20 years, a significant body of research has developed behind the use of natural and engineered wetlands and other soil-based systems for capture and treatment of urban stormwater. Performance is usually measured in terms of water quality, not quantity. Good removal of sediments, suspended solids, nutrients, ammonia, and heavy metals has been reported (USEPA, 1999a,b). In general, engineered wetlands are more effective for stormwater treatment than natural wetlands because the former are specially engineered to accommodate a range of incoming flows (Mays, 2001). Carleton et al. (2001) analyzed data from 35 studies on 49 stormwater treatment wetland systems in order to identify specific performance trends. Long-term pollutant removal is a function of the mean detention time and hydraulic loading rate.

Curbside channels are envisioned throughout OH-007 that divert street runoff away from catchbasins and towards a constructed wetland located downslope (Fig. 2). These 30 cm wide concrete box channels would be situated in the parking lane, adjacent to curbs, and have depths varying from 10 to 30 cm. Metal gratings would prevent car tires, pedestrian feet, leaves

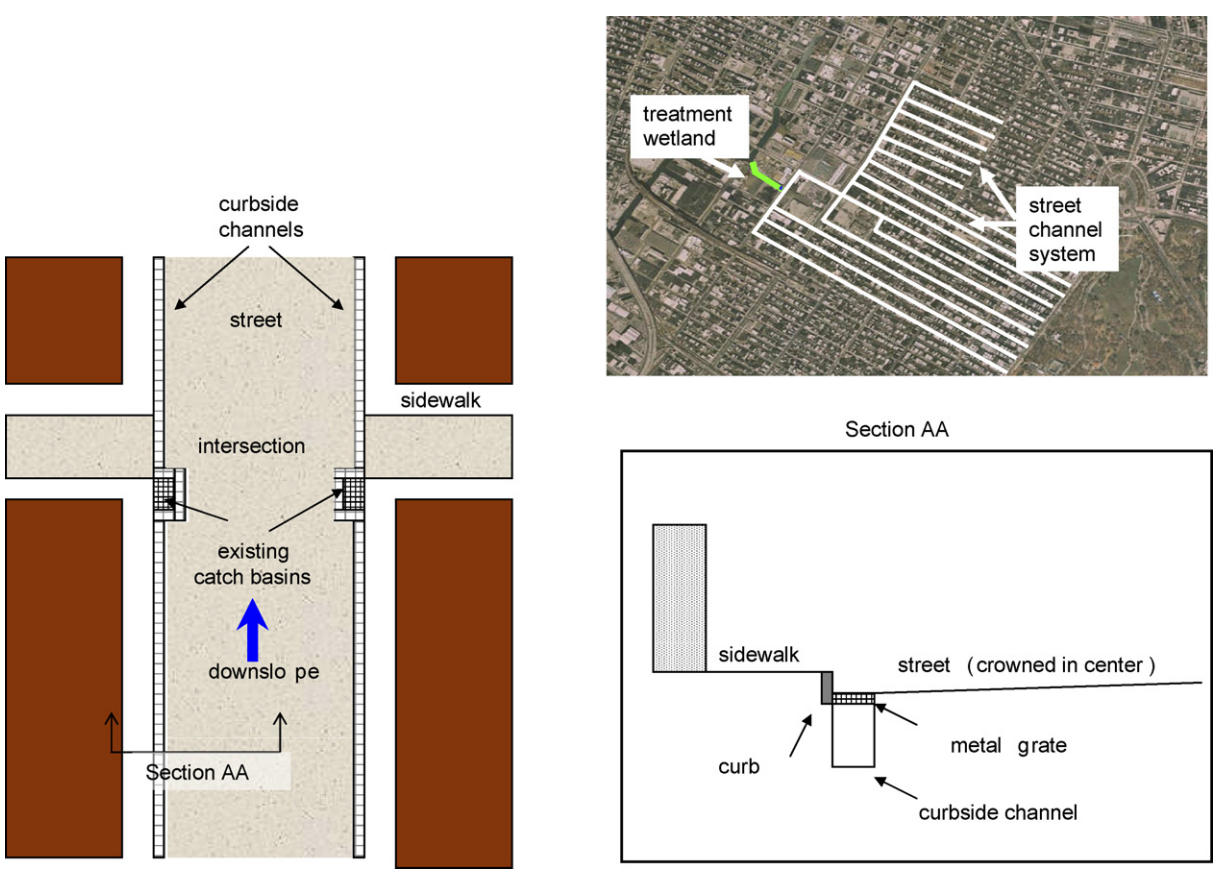

Fig. 2. Treatment wetland and curbside channel scheme.

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and other debris from entering the channels, and allow water to move across intersections in a downslope direction. During extreme rain events, overflows from the channels would be directed to existing catch basins at the corners of intersections. During the more frequent, smaller storms, the network of channels would convey the harvested rainwater to a constructed wetland created at a downslope location, in this case in an underutilized turning basin of the canal. This system is feasible in the OH-007 CSO-shed both because of nearly constant downward slopes towards the Gowanus Canal, and the presence of an underutilized canal turning basin that could become available for a constructed wetland project. For the analysis, we assume that the installation of all curbside channels and wetlands would be on public property, and that the work could be phased into the ordinary schedule of street repaving in the area. Implemented over the sewershed, the channels and wetlands would "take offline" a large portion of the street surfaces in the sewershed, justifying expression of this approach with a reduced runoff coefficient.

3.3.2. Hydrologic analysis

LIDRA data inputs included the 1988 hourly precipitation record from JFK airport and the modeled time of onset of all CSO events during 1988. (The NYCDEP uses 1988 for facility planning purposes, and uses a SWMM-based model to estimate the time of onset of all CSO events.) CSO events can be caused by both short-term intense rainfall and extended periods of moderate rainfall. In Fig. 3, vertical bars indicate 1988 hourly rainfall and symbols represent the total rainfall amount corresponding to the modeled time of CSO onset. Where the symbol is at the peak of the bar, a short, high-intensity storm triggered a CSO whereas when the symbol is higher than the bar, a lower intensity, and longer duration storm was the cause.

In Fig. 4, the cumulative amount of rainfall occurring before each CSO event (including dry periods of up to 3 h) is plotted versus the number of hours over which this rainfall took place.

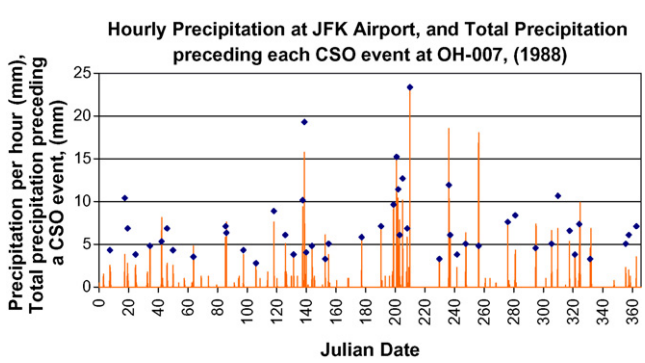

Fig. 3. 1988 Daily hourly precipitation for JFK Airport, and modeled time of onset of OH-007 discharge events during that year. The time of onset of discharge was modeled by NYCDEP using a SWMM-based modeling package. Vertical bars indicate 1988 daily hourly rainfall and blue diamonds correspond to the time of initiation of CSO discharge. The vertical position of the diamonds represents the cumulative precipitation preceding each overflow event. Where the diamond is at the peak of the bar, a short, high-intensity storm triggered a CSO whereas when the symbol is higher than the bar, a lower intensity, and longer duration storm was the cause. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

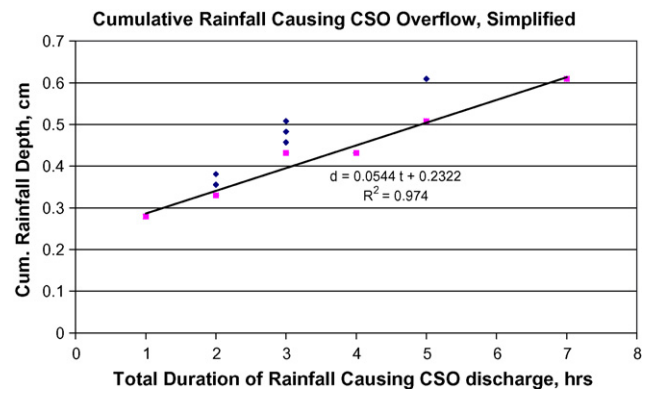

Fig. 4. Cumulative rainfall depths preceding overflows at OH-007. Diamonds represent different CSO events that occurred during 1988. The vertical position of each diamond represents the cumulative depth of precipitation preceding an overflow. The horizontal position represents the number of hours over which that precipitation took place. The magenta diamonds are the lowest, cumulative amount of precipitation that, occurring over a given period of time, caused a CSO. These values were used to generate the regression line. Not shown in this figure are precipitation events that include 1-h rain depths of more than 0.27 cm (since that amount of rain would have triggered a CSO on its own). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Fig. 4 indicates that as little as 0.27 cm of rainfall occurring in 1 h is sufficient to cause a CSO. Rainfall of greater duration, which include 1-h rain depths of more than 0.27 cm are not shown in Fig. 4 (since that amount of rain would have triggered a CSO on its own).

A linear relationship between the duration of rainfall leading up to a CSO, t, and the cumulative depth of rainfall causing CSOs $d_{t,C}$ can be obtained from the data shown in Fig. 4. The lower boundary (denoted as magenta diamonds on the graph) is used to perform the regression since these values represent a sufficient (although not necessary), cumulative depth of rainfall that could result in a CSO. This relationship is expressed with the equation below:

$$d_t = 0.054t + 0.232 \quad (4)$$

The linear relationship ($r^2 = 0.97$) indicates the sewer system's capacity to receive greater cumulative depths of rainfall over increasing storm durations, without overflowing. Eq. (4) is used to determine rainfall depth thresholds that trigger CSOs.

Next, a composite runoff coefficient for the existing watershed, C_{ex}, is computed as a weighted average of the runoff coefficients and areas of surfaces present in the watershed. A component runoff coefficient of 0.9 was used for sidewalks, driveways, and conventional roofs and streets, and 0.1 was used for existing green spaces. Calculated in this way, the composite runoff coefficient for the existing CSO-shed was 0.78.

Using Eqs. (1) and (4) and C_{ex}, a series of threshold, effective peak runoff rates, causing overflows from the existing CSO-shed, are computed. These are listed in Table 5.

These thresholds, in turn, are plugged into Eq. (2) to calculate cumulative depths of rainfall (d_{t,C_p}) which, occurring over a given time, t, would be expected to cause a CSO from CSO-sheds with a range of proposed aggregate runoff coefficients,

Table 5
Computed threshold, effective peak runoff rates, causing overflows from the existing CSO-shed

T (h)	Q (m^3/s)
1	0.87
2	0.52
3	0.40
4	0.34
5	0.31
6	0.28
7	0.26

C_p. Table 6 indicates the component runoff coefficients used to represent LID replacement of constituent areas in this initial simulation. It is noteworthy to mention that representing green roofs and porous pavement with a runoff coefficient of 0.3 is conservative given literature ranges cited earlier for these technologies.

The last step of LIDRA involved re-examining the 1988 rainfall record to determine the number of expected CSO discharge hours for different C_p values. As expected, lower runoff coefficients for LID systems reduce the number of hours during which CSOs are expected to occur.

Ultimately, the *effectiveness* of LID to reduce CSOs is represented by the percent reduction (from existing conditions) in total expected CSO discharge hours. Fig. 5 shows the percent reduction in potential CSO discharge hours as a function of C_p. A log-linear statistical representation of this curve has a good fit ($R^2 = 0.998$):

$$\%\text{Reduction in CSO} = -0.70\ln(C_p) - 0.19 \quad (5)$$

where C_p ranges from 0.40 to 0.78.

The linear model is estimated for a narrow set of C_p to improve the fit over the range that is relevant to potential levels of LID implementation.

Table 6
Runoff coefficients employed for component surfaces during initial model run

Item	Runoff coefficient employed (initial run)
Sidewalks	
Porous concrete	0.3
Ordinary concrete	0.9
Driveways/parking lots	
Porous asphalt	0.3
Ordinary asphalt	0.9
Roofs	
Green roof	0.3
Conventional roof	0.9
Streets	
Street linked to wetland	0.3
Ordinary street	0.9
Existing green spaces	
Parks, lawns	0.1

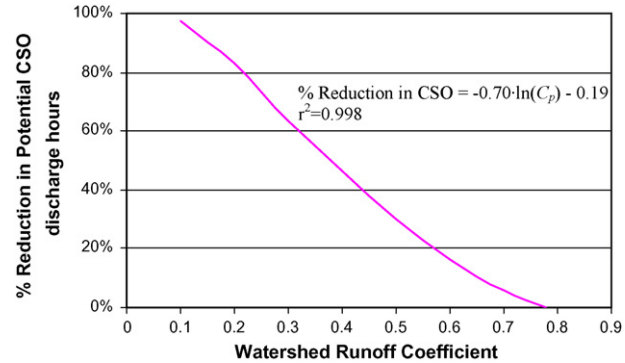

Fig. 5. Percent reduction in potential CSO discharge hours as a function of the aggregate runoff coefficient, C, of the CSO-shed. A zero percent reduction corresponds to the current runoff coefficient, 0.78. A log-linear relationship well represents the curve.

3.3.3. LID effectiveness

Table 7 summarizes the maximum achievable reduction in CSOs expected from each of the LID technologies considered, assuming full implementation of all applicable surfaces and using the conservative performance and cost assumptions of the initial simulation. As shown in the table, implemented alone and to the maximum extent feasible in the CSO-shed, green roofs could conservatively reduce CSOs by about 26%. Porous pavements could generate reductions of approximately 11%, and the curbside channels/treatment wetland, also alone, could reduce CSOs by about 10%.

3.3.4. Economic analysis

LIDRA assumes that a public agency would subsidize the difference in total costs between LID and conventional surfaces, and that the amount of this subsidy can be compared to other government expenditures to reduce CSOs, such as, for example, with centralized infrastructure. Further it assumes that the choice to install a LID system is made when an existing structure (i.e. a sidewalk or roof) requires replacement. For example, when a private property owner must replace her roof, she can choose between a conventional roof or a green roof. The initial simulation assumes that (a) a conventional roof costs US$ 92 m^{-2} and a green roof costs US$ 194 m^{-2}; (b) green roofs would last 36 years and conventional roofs would last 16 years before each needs replacing; and (c) annual maintenance costs for each roof are 1% of the initial cost. In addition, the LCA assumes a discount rate of 7.5%, which is between the 30 year U.S. Treasury Bond Rate of 6.25% and private discount rates of 9.5% as estimated for the real estate sector (Rynne Murphy and Associates Inc., 2005).

Table 7
Initial model run: simulated reduction in CSO discharge resulting from maximum implementation of each LID option

	Modeled percent reduction in CSOs
Green roofs alone	26
Porous pavement alone	11
RWH alone	10

Table 8
Cost data for LID systems

Item	Installation cost (US$ m^{-2})	Annual maintenance cost (% of installation cost)	Use life (years)	Public LID life cycle cost (US$ m^{-2})	Private LID life cycle cost (US$ m^{-2})	Total LID life cycle cost (US$ m^{-2})
Sidewalks						
Porous concrete	43.00	1	40	36	12	48
Concrete	11	1	40			
Driveways/parking lots						
Porous asphalt	65	1	8	74	12	86
Asphalt	11	1	10			
Roofs						
Green roof	194	1	36	85	132	217
Conventional roof	92	1	16			
Treatment wetland/channels						
Curbside channels + wetland	480 m^{-1} [a]	1	30	480 m^{-1} [a]	0	480 m^{-1} [a]

[a] Costs for treatment wetland and channels averages wetland costs over full implementation over all linear meters of channel installation.

The LCA is conducted for a 36-year period to account for the longer durability of a green roof surface. During this period, a conventional roof would be replaced twice with the third resurfacing having a residual value. The results indicate a difference in life-cycle costs of US$ 85 m^{-2}. This value is a subsidy made available by the government to promote this type of LID to interested homeowners.

Data used in the economic analyses of LID systems, including green roofs, and the results are shown in Table 8. Note that the installation costs for green roofs, porous asphalt, and porous concrete are conservative, compared to the literature values cited previously. Due to the limited number of LID installations and installers in the New York metropolitan region, basic assumptions on annual maintenance costs and use life in the analysis were estimated based on interviews with contractors and other knowledgeable persons, published sources, and technical manuals. Cost data for porous asphalt and concrete were obtained from manufacturers. Fixed costs for the treatment wetland included US$ 300,000 ha^{-1} for installation and US$ 1 million for draining the turning basin and installing a retaining wall. To arrive at costs for installation, we assumed that the system would be applied across 126 city blocks and that the wetland would require a barrier wall. Costs for the system can be computed on a linear basis assuming wetland costs are a lump sum in the total. Assumed quantities of units and unit costs for calculating the cost per linear meter of curbside channel include: (a) removal of 126 catch basins (1 per block) at a per unit cost of US$ 360; (b) 5500 m^3 of excavation at a per unit cost of US$ 310; and 29,600 m of channel installation at a per unit cost of US$ 377. The wetland barrier wall was estimated to cost US$ 1 million and installation of the 6500 m^2 wetland was assumed to be US$ 30 m^{-2}. Maintenance costs and durability of the channels are assumed to be no different than normal road surfaces. The LCA analysis of curbside channels is assumed to be additional to normal road repair, which itself is a public cost. Some of the construction costs would occur as regularly scheduled road improvement and maintenance.

Table 8 indicates that the total LCA costs for LID are higher than conventional designs. The public cost is the subsidy that would be provided to property owners to make up the difference between LID installations and conventional surfaces on private land.

3.3.5. *Cost-effectiveness of LID*

The cost-effectiveness of LID is evaluated by comparing the public cost of a particular LID implementation scenario with its performance in reducing CSOs. The curves in Fig. 6 illustrate the cost-effectiveness of each of the three LID technologies, implemented alone and independently in the CSO-shed, and to various spatial extents. LID curves begin at the origin (indicating no implementation) and extend up to a maximum spatial extent of implementation in the CSO-shed. For example, a US$ 23 million public investment in green roofs would yield an 11.4% reduction in CSO discharge.

Fig. 6 indicates that both the porous pavement systems and the treatment wetland/curbside channel scheme would both be marginally more cost-effective than green roofs. These findings

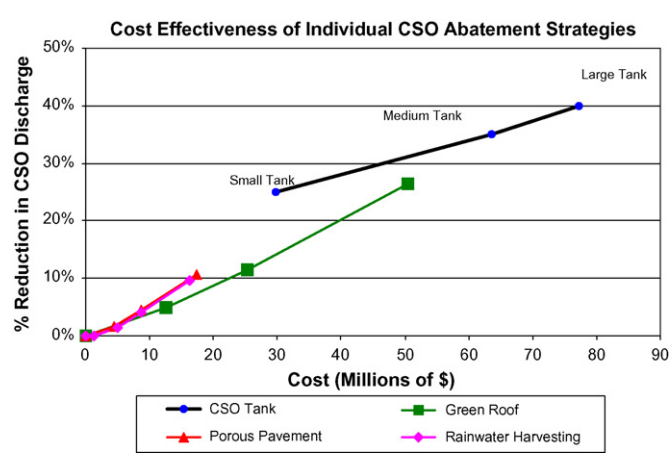

Fig. 6. Cost-effectiveness of individual CSO abatement strategies, implemented to various spatial extents.

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corroborate the findings of a similar study in Toronto, Canada (Dillon Consulting, 2004). However, due to the large area of rooftop surfaces in the CSO-shed, green roofs can lead to significantly higher reductions in CSOs, at maximum buildout.

Also shown in Fig. 6 is the cost-effectiveness curve for CSO tanks developed from NYCDEP data for the OH-007 sewershed. The graph shows three tank sizes (referred to here as 'small', 'medium', and 'large'). The cost estimates represent partial life-cycle costs in which construction costs and annual operation and maintenance costs are included but not land acquisition. It should be noted that land acquisition costs in urban areas can be extremely high, and as such often represent a major constraint on CSO tank feasibility not considered here. Operation and maintenance costs are assumed to be 1.5% of the construction costs. The CSO tank cost-effectiveness curve is presented as a continuous line but in reality, more discrete levels of investment would likely be involved. Also, a minimum investment of US$ 30 million is assumed to be necessary to construct a small CSO tank, that would reduce CSO by 25%.

3.3.6. *Combined LID implementation scenarios*

LIDRA can be used to assess various means of reducing CSOs using LID alone, in combination with other forms of LID, or with a CSO tank. Each LID option can also be implemented incrementally over a range of spatial extents. If funding for the CSO reduction program is phased over time, the greatest results would be achieved by subsidizing and promoting each component CSO reduction technology in order of most to least cost-effective. The rate of effectiveness is simply the marginal increase in percent reduction in CSOs per unit public cost of each tank or LID system. Graphically, this rate of effectiveness is the slope of each of the curves shown in Fig. 6. Such a LID implementation plan is idealized considering that there is likely to be a wide range of actual installation costs and levels of interest from property owners. In addition, efforts to promote several CSO reduction strategies may be pursued in parallel. The results show that the idealized public LID installation investment path would promote (in order) porous pavement, the treatment wetland/curbside channel scheme, and then green roofs.

Although CSO tanks are priced for discrete tank sizes, rates of effectiveness can be inferred. For example, the rate of effectiveness for a small tank would suggest that each US$ 1 million spent yields a 1.2% reduction in CSO (Table 3). However, the medium-sized tank generates an additional 10% reduction in CSO but requires another US$ 35 million. This finding suggests that the rate of effectiveness of a small CSO tank is greater than any of the LID systems, or the medium or large tanks.

3.3.6.1. Scenario 1: CSO tank not feasible. In some urban settings, CSO tanks are not feasible due to land inavailability or other physical limitations, or because of community resistance. In this case, the idealized, least-cost CSO-reduction strategy would begin by dedicating public funds to subsidize the LID system with the highest rate of effectiveness—in this case the porous pavement. The treatment wetland/curbside channels scheme has an intermediate rate of effectiveness and thus would be phased into the CSO-shed next. Finally, green roofs, with the lowest rate

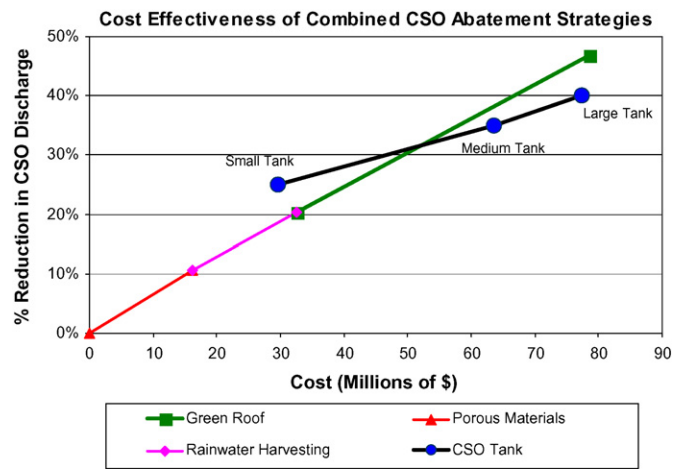

Fig. 7. Cost-effectiveness of combined CSO abatement strategies, beginning with LID.

of effectiveness would be promoted. The cost-effectiveness of this LID implementation strategy is shown in Fig. 7. Of course, if all three LID systems could be implemented simultaneously the time to reach maximum CSO reduction would be reduced. Also shown in Fig. 7, for reference, is the CSO tank cost-effectiveness curve.

3.3.6.2. Scenario 2: CSO tank is feasible. Where CSO tanks are feasible, a key decision for SWM managers would be to determine which CSO-abatement strategies to promote and in what order, given that public funds are often allocated over several years. In this case, the idealized least-cost CSO reduction strategy would construct the small CSO tank first, and then begin funding the retrofit of LID systems into the CSO-shed.

The combined installation of a small CSO tank and LID systems, following a least-cost path, is shown in Fig. 8. In this example, CSO abatement systems are sequentially added beginning with the highest rate of cost-effectiveness (small CSO tank). The cost of the small tank is fixed at US$ 30 million and is thus represented as a vertical line. The LID systems would then be phased into the sewershed in order of increasing rate of cost-

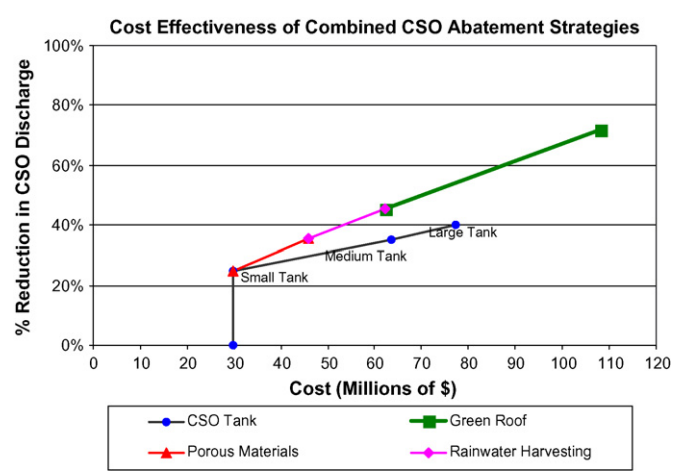

Fig. 8. Cost-effectiveness of combined CSO abatement strategies, beginning with small CSO tank.

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Table 9
Sensitivity analysis of LID cost-effectiveness compared to CSO tanks by tank size

LID system	Installation cost (US$/m^2)	C		
		0.1	0.3	0.5
Green roof	172			
	194			
	215			
Porous Surface (concrete/asphalt)	54/32			
	65/43			
	75/54			
Rainwater harvesting (unit: linear m)	110			
	146			
	183			

The relative cost-effectiveness of LID (given parameter value combinations for LID) compared to particular tank size is indicated by the shading of a cell in the scenario matrix. Cells that are more cost effective than tanks of different sizes have lighter shadings.

Cell shading key:

LID is more cost effective than all tanks
LID is cost effective when implemented after constructing a small tank
LID is cost effective when implemented after constructing a medium sized tank
LID might only be cost effective after construction of a large tank

effectiveness, or all together if sufficient public funding were available.

Fig. 8 also shows how this optimal SWM investment path compares with that of sequentially larger CSO tanks. Phasing LID systems into the sewershed once a small CSO tank has been constructed is a more cost-effective strategy of reducing CSOs than building medium or large size CSO tanks from the beginning. That is, for any level of investment beyond the cost of a small tank, a hybrid tank/LID strategy would be more cost-effective than a larger tank, given the assumptions used in this initial simulation.

3.3.6.3. Sensitivity analysis on costs and performance of LID. To generalize the above findings, a sensitivity analysis is performed on the LIDRA results considering a range of levels of performance (range of C values) and range of costs for each LID option. The cost-effectiveness of each LID system is compared individually against that of CSO tanks of different sizes. In this way, we use the sensitivity analysis to compare a CSO reduction strategy featuring only tanks to a hybrid one that promotes LID technologies with variable costs and levels of performance. In the sensitivity analysis, both the runoff coefficients used to represent LID effectiveness, and the LID installation costs are varied. In the original analysis, a runoff coefficient of 0.3 was assumed for each LID option. Actually, runoff coefficients vary with antecedent moisture, various design parameters, and other factors. In the sensitivity analysis, runoff coefficients for all three LID technologies are varied from 0.1 to 0.5. Installation costs are varied over a hypothetical range (approximately 20% up and down) for each system.

The results of the sensitivity analysis are presented in Table 9. The cost-effectiveness of individual LID technologies compared to CSO tanks of various sizes are represented by shading of the matrix cells. Cells with increasingly darker shades indicate that LID performs less cost-effectively compared to larger tanks.

Table 9 indicates that LID systems may be more or less effective than CSO tanks of different sizes depending on their installation cost and runoff coefficient (performance) parameters. Individual LID technologies are more cost-effective than all of the tanks considered in this analysis, provided that the assumed runoff coefficients and installation costs are on the low end of the ranges tested (lightest-shaded boxes). In such cases, a least cost path to reducing CSOs would rely on LID technologies exclusively, and involve construction of tanks only after all LID opportunities have been exhausted, if additional reductions in CSOs are sought. For example, if green roofs in the study area cost US$ 172 m^{-2} to install and perform at $C = 0.1$, then it would make sense for government expenditures to be used to begin subsiziding the retrofitting of green roofs into the study area, before building any tanks (or subsidizing the next most cost-effective forms of LID).

The sensitivity analysis suggests that at higher costs and runoff-coefficients, however, some of the tanks considered in the analysis are more cost effective than specific LID technologies (darker shaded boxes). In these scenarios, a least cost path to CSO reduction would involve LID *and* a tank. For example, if moderately performing (i.e. $C = 0.3$) porous concrete costs US$ 54–75 m^{-2}, the most cost effective approach to CSO reduction would be to construct a small tank, and then start phasing in LID. This case is analogous to the case shown in Fig. 8.

Only at the highest cost and poorest performance scenarios do situations emerge in which LID does not appear cost effective, as compared to any of the tanks considered in this analysis.

4. Discussion and conclusions

LIDRA is a simple approach to assessing the potential cost-effectiveness of public investments in LID as a means of reducing CSOs. Simplifications inherent in LIDRA include representation of urban surfaces with uniform runoff coefficients, the assumption of uniform rainfall intensity over the drainage area, and the use of hourly rainfall data and modeled (not observed) time of onset of CSO discharge. In addition, the influence of tides and wastewater volumes on CSO is not explicitly addressed in this model.

Verification of LIDRA results with actual data would require the availability of measurements of the frequency and volume of CSOs before and after an intense effort to building LID into an urban watershed. The authors are aware of no such data set, and thus verification of LIDRA with real data is impossible at this time.

Verification of LIDRA findings against conventional H&H models is possible. Because construction of a high resolution H&H model of an entire CSO-shed would require significant time and resources, one possibility would be to focus verification efforts on a small edge portion of a CSO-shed. The reason for selecting an "edge" would be to focus on a well-defined, small-scale study area, not influenced by sewer flows originating further uphill. Once the existing conditions H&H model domain has been developed, it could be calibrated using monitored sewer flow data. The calibrated existing conditions model could then be modified to simulate the retrofit of LID technologies into the study area. The latter would involve devising means of representing LID in the model, a task that could be accomplished by calibrating separate, even smaller scale models to performance data from existing LID systems. These nested modeling efforts could then be used to develop a methodology to represent LID implementation in urban scale H&H modeling efforts, and the results could be correlated with cost figures and compared to LIDRA results.

LIDRA results could be significantly improved if more data on LID performance, cost, and public acceptance were available. Such data could be incorporated into the model using monte-carlo techniques, which would more realistically represent the uncertainty associated with each of these parameters, and permit presentation of the model results in a probabilistic framework. More experimental research documenting the runoff coefficients of different LID technologies under varying conditions could be used to improve LIDRA, while also serving the dual purpose of helping developers and regulators to compare LID in conventional engineering terms to other urban stormwater control techniques. With more LID installations, more refined estimates of installation, operation, and maintenance costs will also become available.

LID public acceptance studies would focus on private property owner interest in and willingness to pay for LID. Implicit in LIDRA are the assumptions that property owners would not be willing to pay a premium for LID, but that they would adopt LID if it was cost neutral to them. In a survey mailed to 300 property owners in the OH-007 drainage area (17% response rate), 79% of respondents indicated that they would be willing to accommodate porous pavement on their property if it cost no more than regular pavement. Seventy-seven percent of respondents would be willing to house a green roof on their property if it cost no more than an ordinary roof (Montalto et al., 2007b). These kind of surveys could be used to represent property owner decisions into LIDRA, so as to use the model to predict the probability of LID adoption in response to different levels and kinds of public subsidies.

This said, as it is currently formulated, LIDRA requires fewer input parameters than more complicated distributed hydrologic and hydraulic models such as SWMM, and as such can be used as a SWM planning tool to rapidly assess the potential cost-effectiveness of LID in urban watersheds. To our knowledge, no other planning tool of this kind currently exists. Across watersheds, LIDRA can be used to prioritize government spending on SWM, specifically by helping to identify specific watersheds where LID systems would be most helpful in attaining CSO abatement goals. Within watersheds, LIDRA could be used to estimate specific levels of LID technology implementation required to achieve targeted reductions in CSOs. Application of a LIDRA analysis to a particular site would require only the availability of digital maps of the targeted drainage area, a precipitation record and corresponding time series representing the onset of all CSOs, a simple site inventory involving a building stock analysis to identify locally relevant LID options, and some locally generated estimates of LID and conventional CSO abatement infrastructure costs. Because of its simplicity, the total cost of a LIDRA analysis would be relatively low (under US$ 25,000 for a comparably sized drainage area to OH-007), compared to other engineering and planning studies.

The results of this LIDRA application suggest that LID can be a useful component to SWM in dense, urban areas served by combined sewers. Under a range of cost and performance assumptions, LID systems applied across OH-007 could potentially achieve cost effective reductions in CSOs at costs that are competitive or better than CSO tanks.

The case study suggests that LID programs are best implemented and most effective in the context of integrated watershed planning efforts that involve public agencies working with private property owners. Public–private partnerships that promote the use of LID to control CSOs are reasonable because while much of the land that contributes runoff is privately owned, and the liability for CSOs rests with the government, the general health of the urban watershed and lies in the interest of all. In addition, such partnerships could dovetail nicely with other efforts to promote public participation in CSO control efforts (also mandated by federal policy).

Several issues do need to be addressed, however, if LID is to become a viable approach to reducing CSOs. First, if numerous LID installations distributed throughout a drainage area represented a particular sewer district's CSO abatement program, some means of quality control would need to be imposed on the construction, operation, and maintenance of these systems. While operation and maintenance of centralized facilities can be centrally controlled, a decentralized CSO abatement program would require quality control inspectors routinely visiting LID installations located on private property. The training of inspectors and site access issues would need to be addressed. Secondly, assuming that LID construction, operation, and performance could be ensured, sewer district managers would need to be confident that the time required to achieve a level of LID implementation corresponding to CSO reduction targets would fit within the compliance timetables set by CSO control policy. If not, they might opt towards centralized CSO reduction strategies, even if they are less cost-effective than LID, simply to reduce the chance of penalties for non-compliance. Finally, a CSO abatement strategy emphasizing LID might also need to be accompanied by revisions to local building codes, zoning

and other regulations, which often create significant obstacles to developers who implement LID.

Where these issues can be overcome, LIDRA could be used to create a pilot public subsidy program that, like the Portland Downspout Disconnect program cited earlier, sets a specific number of dollars available to property owners for every square meter of porous pavement, green roof, or other relevant LID technology installed. LIDRA could be used to estimate the levels of LID adoption that would be required to achieve a particular CSO reduction goal in the drainage area, and then to structure appropriate public subsidy programs. These would create incentives to construct the most cost-effective LID applications first, decreasing the total cost of the program. The public subsidy amount might be regressive in time, so as to encourage individual property owners to replace surfaces sooner. Subsidies could become available as property owners make site improvements, or potentially also when properties change hands.

In conclusion, it should also be mentioned that introducing LID into urban areas is also a way of improving the overall environmental quality and footprints of growing cities. In addition to their runoff reduction benefits, LID technologies facilitate the reuse of harvested rainwater, reducing the demand for and O&M costs of municipal drinking water supply systems. By reducing sheet flow and runoff velocities and promoting infiltration, LID also reduces the potential for soil erosion, while recharging aquifers and the base flow of urban streams. When LID technologies promote evaporation, they can reduce building energy demands, mitigate the urban heat island effect, and on a large scale help to reduce urban rain shadows. Finally, vegetated LID technologies increase biological productivity—an essential step towards greener cities.

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