Probabilistic green infrastructure cost calculations using a phased life cycle algorithm integrated with uncertainties

Ziwen Yu, Franco Montalto and Chris Behr

ABSTRACT

Green infrastructure (GI) is often considered a cost-effective approach to urban stormwater management. Though various models have been created to simulate the life cycle cost (LCC) and present value (PV) of GI investments, decision-support tools are still few. This paper introduces a probabilistic GI cost estimation algorithm built into the Low Impact Development Rapid Assessment (LIDRA) model. This algorithm tracks annual and cumulative costs associated with the construction, operation and maintenance (O&M), and ultimate replacement of GI systems. In addition, the algorithm accounts for uncertainties in cost drivers, such as a GI's useful life (until replacement), capital and annual O&M costs, inflation, and interest rates. Net present value (NPV) is used to normalize future money flows and cumulative costs of different GI investment scenarios into a comparable current year cost equivalent. Demonstrated at the block scale, the results of the LIDRA algorithm are compared to an MS Excel-based computation of average costs. Variations of uncertainties are then integrated and further explored using an alternative implementation rate. This algorithm is a way to evaluate GI costs considering physical, socioeconomic and life cycle dimensions.

Key words | green infrastructure, life cycle cost, low impact development, net present value, stormwater management

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INTRODUCTION AND BACKGROUND

As a stormwater source control strategy, green infrastructure (GI) was first introduced as low impact development (LID) and applied in Prince George's County, MD (Prince George's County 1999). The stated goal of GI is to attempt to restore natural hydrological processes through decentralized application of green roofs, porous pavement, bioswales, and other stormwater source controls throughout urbanized areas. Because of its many perceived ancillary benefits and lower cost compared to centralized, end of pipe stormwater management approaches, GI has been formally adopted by an increasing number of stormwater utilities as a key component of controlling the impacts of stormwater runoff. In a $1.6 billion dollar plan to be implemented over 20 years, New York City has committed to using GI to manage the first 25 mm of stormwater runoff over 10% of the impervious surfaces in portions of the city served by combined sewers (Bloomberg & Holloway 2010). At a similar level of investment, Philadelphia's GI plan will manage runoff from 47% of the impervious surfaces in its combined sewer district over a 25-year period with GI (Philadelphia Water Department (PWD) 2011). GI is also a key component of the control of combined sewer overflows (CSOs) in Washington, DC (District of Columbia Water and Sewer Authority 2013). It was first legally approved as an approach for control of CSOs in Syracuse, NY in 2009 (Knauss 2009).

Published GI cost–benefit analysis (CBA) studies can be grouped into three categories based on how GI values and costs are defined (ECONorthwest 2007; Garmestani *et al.* 2011). The first category of studies focuses on the initial

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installation costs (ICs) of GI only, which are often compared to that of conventional infrastructure (US EPA 2005; Langdon 2007; Vanaskie *et al.* 2010). The second category also considers the operation and maintenance (O&M) costs of GI throughout its useful life (McGovern & Jencks 2010; Vanaskie *et al.* 2010; Cohen *et al.* 2012). A third category attempts to quantify the monetary value of both the costs and varied environmental benefits of GI (MacMullan *et al.* 2009; Foster *et al.* 2011; Spatari *et al.* 2011).

Until recently, most attempts to evaluate the costs and benefits of GI were generally hindered by the availability of requisite data sets, and had to be preceded by an extensive period of data collection and/or formal cost estimation. Now that implementation of GI programs is well underway in many cities, more data is becoming available, and more elaborate costing exercises can be attempted. Life cycle cost (LCC) calculation procedures, for example, represent one of the best means available to evaluate the 'net' present value (NPV) of investments including installation, O&M, replacement, and disposal of infrastructure projects over a given planning period. Fuller (2010) provides an introduction to LCC analysis that includes a comprehensive list of the key components that are transferable to infrastructure projects. Wong *et al.* (2003) conducted a LCC analysis to assess the value of roof garden by considering IC and O&M cost. Peri *et al.* (2012) advanced the method by including the replacement cost of green roofs associated with a green roof project. These LCC studies, however, are performed deterministically (CNT 2009; Houdeshel *et al.* 2009; Reynolds *et al.* 2012) and do not consider the uncertainties associated with costs, rate of implementation, and broader financial parameters like inflation and interest.

Bianchini & Hewage (2012) estimated the benefit–cost of green roof in terms of NPV from both personal and socio-economic perspective and statistically compared different factors. Consideration of such factors requires quantification of uncertainty using probabilistic approaches. As pertains to GI, this work is in its infancy. No other published research directly addressing uncertainty of GI cost and effectiveness assessments was found in the literature.

This paper introduces a probabilistic, phased LCC calculation process that can be used to evaluate the NPV of GI costs of multiple implementations. The algorithm tracks ICs, O&M costs, and residual costs (RCs) of different GI technologies, implemented at different rates, over different spatial domains over a pre-defined 30-year planning period. This particular planning period was selected to be commensurate with the implementation horizons of the GI plans cited previously, and also because of its common use for large scale benefit–cost analyses in the US (OMB 1992). The algorithm is used to convert future annual money flows associated with building, operating, maintaining, and replacing complex, user-specified GI plans into a present year's dollar value, hence the term PV. An NPV is computed when determining the difference in present value costs between two GIs. Using Monte Carlo (MC) procedures, uncertain parameters are drawn from both user-specified, expert opinion, and derived distributions of data. Multiple realizations are performed and ranges of predicted costs are generated.

This algorithm is built into the Low Impact Development Rapid Assessment (LIDRA), a planning level model developed by the authors and available for free at www.lidratool.org. After introducing the algorithm in detail, a hypothetical case is presented to demonstrate application of the algorithm through LIDRA. Uncertainties associated with GI cost and implementation rate are investigated in the analysis of the model results. Discussion and conclusions are made at the end.

METHODOLOGY AND DATA SOURCE

Overview of LIDRA

As background to the use of the LCC algorithm in LIDRA, a brief overview of the model is provided. All surfaces in the study area are represented as one of two kinds of urban hydrological response units (UHRUs), parcel UHRUs and street UHRUs. Parcel UHRUs represent roofs, driveways, and yards. Street UHRUs represent streets, sidewalks, and intersections. The UHRUs are situated in land use categories, each of which is defined by user-defined rates for GI implementation. Due to lack of information and drastic differences across different projects even in close locations, the implementation rate is assumed linear over the 30-year planning period as a simple start for a GI project design. Implementation of GI on the parcel UHRUs is defined as 'adoption rate', while implementation of GI on the street UHRUs is defined as 'repaving rate'. The appropriate implementation rate is used to define the fraction of each UHRU that is greened (i.e. hydrologically converted from the baseline condition to the user-defined GI condition) each year. In most cases, each UHRU will be greened gradually over several generations, where a generation refers to the GI installed on a particular UHRU during a particular year.

This paper focuses exclusively on the LCC algorithm used by LIDRA to track the cost of GI systems implemented on the parcel and street UHRUs throughout a 30-year planning period. Other publications describe in detail the relational database utilized by LIDRA to store information about the UHRUs and land use categories (Aguayo *et al.* 2013), a cost-effectiveness uncertainty investigation on GI projects (Montalto *et al.* 2011), a stationary precipitation generator for climate uncertainty assessment in GI hydrologic performance modeling (Yu *et al.* submitted), GI cost-effectiveness assessment using LIDRA (Yu *et al.* 2010), the model's underlying rainfall-runoff model, a non-stationary precipitation generator for modelling climate change uncertainties, and the application of LIDRA on a real watershed case to model the CSO risk reduction (Yu 2015).

Uncertainties in cost calculation

The cost of a municipal GI program is determined by physical, socioeconomic factors, many of which cannot be known with certainty when considering long-term implementation periods over relatively large spatial areas. Relevant physical factors include the dimensions of individual GI systems, the area available for its application, and other physical conditions (e.g. bedrock or high water tables) that constrain implementation. Uncertain socioeconomic factors include: (1) the decisions regarding where and at what rate GI is implemented; (2) geographical distribution of cost; (3) the variability associated with different GI designs. For example, the same GI type could cost differently on two different sites due to differences in where materials are procured and local labor costs. Both ICs and annual O&M costs can also vary significantly from year to year, significant given that GI programs are typically implemented gradually over time. The uneven rate of implementation makes the final total program budget a complicated variable that sums up generations of initial and recurring costs incurred over time and space. In addition, external economic factors, such as the inflation and interest rates, can have a large influence on the nominal amount annual cash flows to implement GI. Their impacts should also be investigated.

Because GI implementation is fundamentally complex, involving multiple stakeholders and new technologies, uncertainty must be explicitly considered in projections of GI cost-effectiveness. As described in more detail below, LIDRA quantifies parameter uncertainty with triangular distributions in which mode, upper and lower bounds for unit costs for ICs, O&M costs and useful lives are each derived from national datasets compiled by the Center for Neighborhood Technology (CNT) (CNT 2009). Financial parameters are assumed to take on a symmetric triangular distribution with mode equal to user specified values associated with a 2.5% variation on each side (5% total). LIDRA performs 100 realizations of each online simulation to characterize the statistical variability possible in the results. To fully investigate the uncertainties, offline simulation with more iterations can be done by contacting developers.

Conceptualization of NPV for phased implementation of GI

LIDRA computes LCCs associated with GI using standard methods to discount future cash flow analysis to current year. The social time preference of future cash flows is captured by a discounting rate, d, that reflects wider socioeconomic and investment conditions. Discounting rates are usually set exogenously for most analyses of capital investments and are defined in 'real' terms to avoid additional assumptions on future inflation rates. In this paper, it is defined by the assumed annual inflation rate, i, and the assumed interest rate, r, as per Equation (1) (Eisenberger *et al.* 1977):

$$d = \frac{1+i}{1+r} \tag{1}$$

where $d =$ discounting factor; i = inflation rate (%); and $r =$ interest rate (%).

Discounting converts any future initial capital and recurring expenses during operation, as well as any residual value (RV) of GI assets at the end of the planning period, to current year dollars. To establish a convenient planning horizon for analytical purposes, the cost of a GI project is computed by subtracting a RV of cost from the total investment in present value (PV), as described in Equation (2). t is defined as the years past since the beginning of a GI's useful life or life time. The PV calculation is relevant for any time period. If a system is implemented in year 25, it is first recognized as a standard discounted value for that year, which includes capital and residual, and future O&M up and until the planning horizon. Then, since that is a cost that would be realized in year 25, a discount should be applied again to bring it to actual PV.

A GI typically only functions for a certain period of time under proper and regular maintenance. For example, the plastic for a rain barrel will be aged when exposed to air and sunlight over time. It has to be replaced after a certain period (e.g. 20 years) to keep its performance in managing stormwater. The performance of the vegetated GIs could be affected by the stormwater runoff itself in terms of erosion. For instance, a road-side swale can lose its soil washed away by a summer thunderstorm, the bank of a rain garden ponding area can be eroded over time and mitigate its ponding capacity, etc.:

$$NPV = \sum_{t=1}^{p} FV \cdot d^{t-1} - RV \cdot d^{p} \tag{2}$$

where NPV = net present value of a project ($/area); FV = future cost ($/area); RV = residual value of cost ($/area); t = years from the beginning of a useful life, if relevant; p = planning period (year). RV is computed as the fractional cost of the installation cost, based on the remaining years left in the useful life of the GI, as per Equation (3):

$$RV = IC\frac{s}{l} \tag{3}$$

where IC = installation cost ($/area); l = GI useful life (year); s = number of years after the end of the planning period (i.e. after the end of the 30 years) during which the GI facility is expected to function (year). Splitting the components of future value, FV, the NPV can be rewritten as:

$$NPV = IC + \sum_{t=2}^{p} AC \cdot d^{t-1} - RV \cdot \mathrm{d}^{p} \tag{4}$$

where AC = O&M cost (annual cost) ($/area).

However, all GI systems do not have the same useful life. If the useful life of a particular GI system is less than the 30-year planning period, one or more replacements may be necessary for sustained performance of this GI over the planning period. Including replacement costs, the equation representing NPV of a GI system is further modified as:

$$NPV = \sum_{m=0}^{\lfloor p/l \rfloor} \left(IC \cdot d^{ml} + \sum_{t=2}^{FT} AC \cdot \mathrm{d}^{t-1+ml} \right) - RV \cdot d^{p} \tag{5}$$

$$FT = \begin{cases} l & if\ p \geq l(m+1) \\ p - lm & if\ p < l(m+1) \end{cases}$$

where m = number of replacements within the planning period; FT = number of years in the useful life before the end of the planning period (year).

Only the RV of the last generation of GI is computed since all the earlier generations are assumed to have been replaced during the planning period.

A further consideration in GI cost calculating is the fact that GI implementation will likely occur over multiple years (e.g. due to community engagement, institutional bureaucracy, contractor mobilization, budget limitations, etc.). Equation (5) can be further modified to consider phased implementation over the planning period. We introduce an implementation phase, Aj, defined as the area that is greened in a particular year, so that the NPV of a particular generation of GI implemented in year j can be expressed as:

$$NPV_j = \sum_{m=0}^{\lfloor (p-j)/l \rfloor} \left(IC \cdot d^{ml+j} + \sum_{t=2}^{FT} AC \cdot \mathrm{d}^{t-1+ml+j} \right) - RV \cdot d^{p} \tag{6}$$

$$FT = \begin{cases} l & \text{if } p \geq l(m+1) \\ p - j - lm & \text{if } p < l(m+1) \end{cases}$$

where $j =$ number of implementation generation; $NPV_j =$ NPV of implementation in year j ($).

Further since GI ICs and O&M costs are available on a unit basis, the total NPV of the whole project can be written as:

$$NPV = \sum^{(NPV_j \cdot A_j)} \quad (7)$$

where $A_j =$ area of implementation in year j (acre or m^2).

As an example, Figure 1 graphically depicts the costs associated with a GI implementation project that occurs over three years (e.g. a 33% implementation rate) on a one hectare area. The IC of this particular GI for a single implemented generation is assumed to be $60/$m^2$·yr, the corresponding O&M cost for each generation in every year is assumed to be $20/$m^2$·yr, and its useful life is assumed to be 20 years. We further assume a 2% inflation rate (based on 2000–2012 Consumer Price Index (CPI)) and interest rate of 5% (based on 2000–2012, 30-year US Government bond interest rate) respectively (US Department of Labor Bureau of Statistics 2016; US Federal Reserve System Statistical Release 2016).

Figure 1 reveals a GI program implemented in three phases (over years 1–3 of the program). The columns represent annual expenses to a hypothetical stormwater utility including ICs and O&M expenditures in each year. ICs only appear during the first year of the life cycle of each generation of GI (year 1, 2, 3 and 21, 22, 23), while the O&M costs are incurred for all subsequent years of the useful life. In present value terms, future costs decline because of the effect of a real discounting rate which reflects society's time-value of money (i.e. future costs are less valued in present terms than current costs). In the 31st year, the first year after the end of the planning period, the RV of each implementation is calculated with a negative sign. The cumulative curve (on the secondary axis) presents the PV of the total cost of all implementations completed in the past years to support the whole project. In the 30th year, it achieves the highest point which indicates the PV of the total investment for the project to be functioning during the planning period. It subtracts the RV to achieve a NPV. However, this is a convenient way to see the net value of a project investment and does not mean that the RV could be paid back. The meaning of a PV amount is equivalent to an amount of money that in year 1 would need to be placed in an interest bearing account (at an interest rate equal to the discount rate) to pay for the entire project.

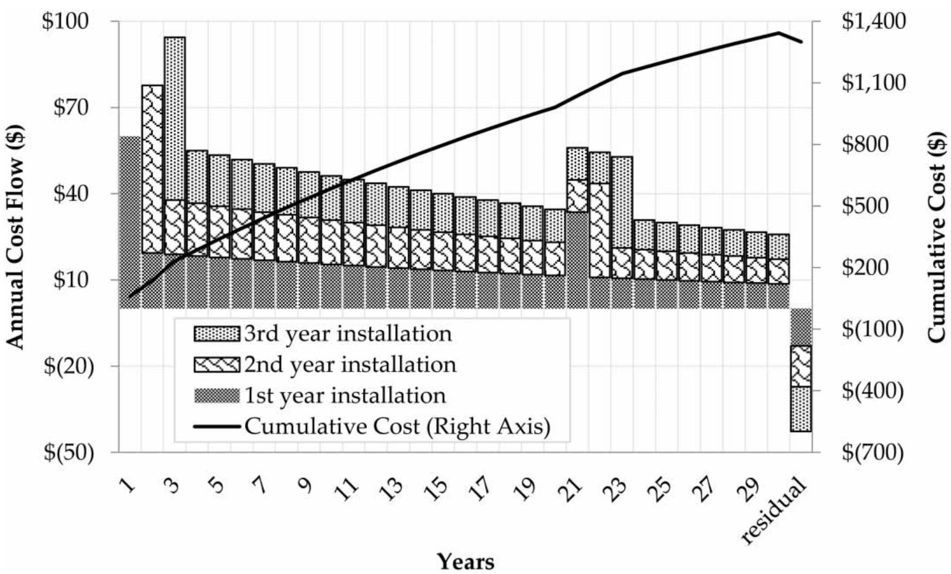

Figure 1 | Sample of NPV applied with life cycle and phased implementation.

Computation of NPV using LIDRA

A flow chart describing the three main components of the LCC algorithm is illustrated in Figure 2. The left box, K (UHRU), shows how unit costs are estimated for each generation of GI implemented on a particular UHRU. The middle box, I (Land Use), demonstrates how uncertain GI implementation rates are tracked throughout the simulation. The right box, D (Project), presents the procedures to generate the discounting (D) factor which is used to convert all annual unit costs to PV for the whole project. Each of these three components of the LCC algorithm is described in detail below. Where invoked, probabilistic Monte Carlo procedures are designated by MC.

Probabilistic definition of unit costs

The left box, K (UHRU), in Figure 2 describes the procedure used to probabilistically define the useful life associated with each generation of GI installed on a particular UHRU, and its annual unit costs. These values are derived from national values published by the CNT (see details in Table 1) (CNT 2007). Each time that a new generation of a particular type of GI is implemented on a particular UHRU, MC procedures are used to draw a unique useful life for that generation from a symmetric triangular distribution based on CNT's low and high values. It is true that the GI cost is related to many local scale parameters, such as legal, construction material, implementation intensity, etc. To keep the simplicity of LIDRA, these parameters are avoided. In

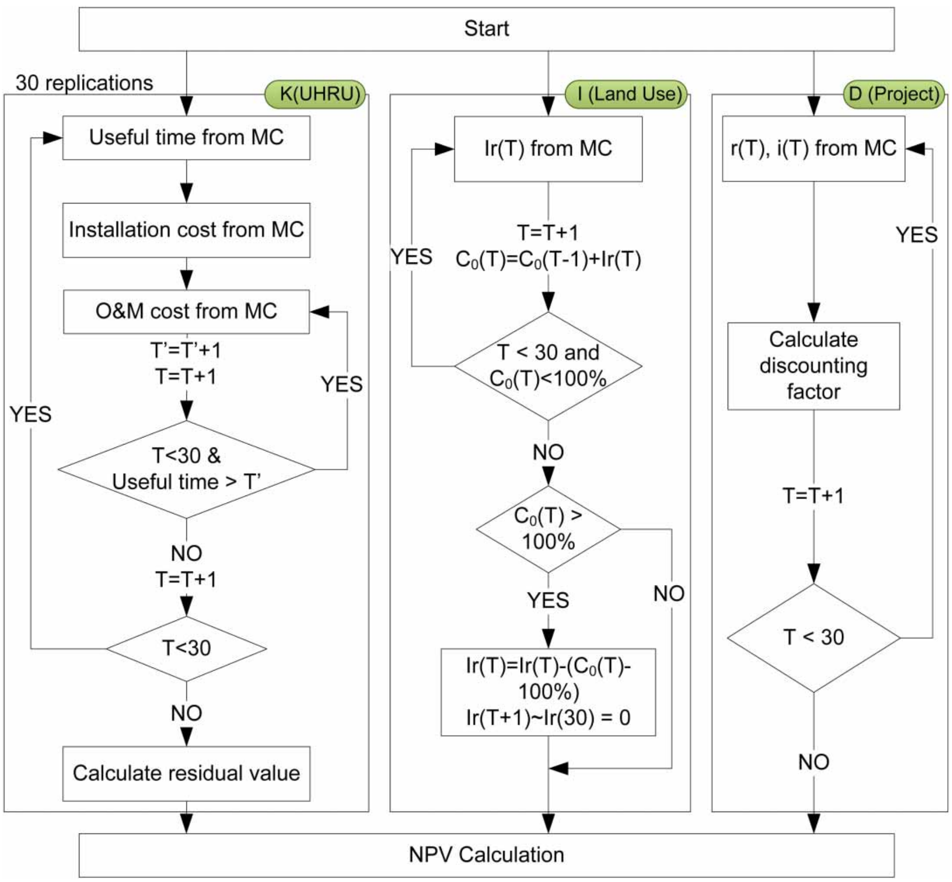

Figure 2 | Flow chart of overall life cycle cost algorithm in which the left box, K (UHRU), depicts the procedure for selecting costs of UHRUs, the middle box, I (Land Use), depicts the procedure for selecting the implementation rate for land uses, and the right box, D (Project), depicts the procedure used to select discounting factors during the planning period for the whole project. (K (UHRU) = implementation expense matrix; I (Land Use) = implementation rate matrix; D (Project) = discounting rate matrix; T = past years in a planning period; T' = past years in a useful life; Ir = Implementation rate of a land use; Co = cumulative GI coverage percent in a land use; r() = interest rate function of time; i() = inflation rate function of time.)

Table 1 | GI data table

Name	Initial cost low ($/m^2)	Annual cost low ($/m^2)	Life time low (yr)	Initial cost high ($/m^2)	Annual cost high ($/m^2)	Life time high (yr)	Source
Tree	10.76	8.61	25	263.93	8.61	25	CNT (2007)
Rain barrel/cistern	6.67	0.11	20	42.19	0.32	20	
Downspout disconnection	3.23	0.01	30	12.38	2.69	100	
Permeable pavement	43.06	0.06	20	141.01	2.05	50	
Curbside swale	897.71	0.16	30	4,972.92	15.61	50	
Rain garden	8.37	0.15	25	512.58	15.61	50	
Blue roof	43.06	0.00	20	261.02	0.00	20	
Green roof	129.17	1.08	25	579.21	31.11	40	

special cases, users can contact the developers with the specific cost information to run a specific simulation offline.

MC procedures are also used to assign a unit IC to that particular GI generation, from a symmetric triangular distribution based on CNT's costs. Using the same procedure, new unit O&M costs for that GI generation are generated each year for each generation of GI. K (UHRU) in Figure 2 shows the loop used to keep track of all of the unit costs associated with each GI generation. T is a number between 0 and 30 that depicts the number of years that have passed since the beginning of the simulation. T' is defined as the number of years that have passed since that particular GI generation was installed. The need for replacement is determined by comparing T' with the useful life of that particular GI generation. The entire loop is halted when $T = 30$. Once the loop is halted, the RV (if any) of that GI generation is computed.

Probabilistic definition of implementation rates

The middle box, I (Land Use), in Figure 2 depicts the procedure used to define the GI implementation rates for each land use in LIDRA. Land uses are used in LIDRA to specify clusters of UHRUs assumed to have identical GI implementation rates. Each land use is assigned an adoption rate that is applied to all parcel UHRUs within it, and a repaving rate applied to all street UHRUs in it. For a given land use category, Ir represents the percent of that land use that is greened each year. To reflect the uncertainty in implementation rates, LIDRA then uses MC procedures to draw a unique implementation rate for each year of the simulation for each land use category from a symmetric triangular distribution centered on the user-specified value but extending ±10% of the input value. In this way, random implementation rates are generated for each year for each land use category. The cumulative GI coverage (C_O) in the land use category is tracked through time to check whether full build out has been achieved. Note that if full build out occurs before $T = 30$ (e.g. the end of the simulation), the final year's implementation rate is selected deterministically to ensure that implementation never exceeds 100% of the UHRU area.

Probabilistic definition of discount rates

The right box, D (Project), in Figure 2 presents the procedure used to select the discounting factor used for the whole project for each year of the simulation. Users define an inflation rate, i, and an interest rate, r, at the onset of the simulation. The user-specified values for these two parameters are assumed to be the mode values in a symmetric triangular distribution encompassing ±2.5%. MC procedures are used to select a unique inflation and interest rate for each year of the simulation. These values apply to all GI types on all UHRUs in all land use categories.

Matrix storage of probabilistic values

The randomized parameters generated in procedures K, I, and D are organized as four matrices. An expense matrix, K (UHRU), is defined for each unique UHRU in the simulation. Two matrices of I (Land Use) are developed for each given land use category: one representing the adoption rates used for GI on all parcel UHRUs, and one representing the repaving rates used GI on all street UHRUs. One discounting rate matrix, D (project), is defined for the whole project in the simulation. The members of these matrices are shown below.

$$K(UHRU) = \begin{bmatrix} C_1^1 & 0 & 0 & \dots & 0 \\ C_2^1 & C_2^2 & 0 & \dots & 0 \\ C_3^1 & C_3^2 & C_3^3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_{30}^1 & C_{30}^2 & C_{30}^3 & \dots & C_{30}^{30} \\ -RV^1 & -RV^2 & -RV^3 & \dots & -RV^{30} \end{bmatrix}$$

$$I(Land\ Use) = \begin{bmatrix} Ir_1 \\ Ir_2 \\ Ir_3 \\ \vdots \\ Ir_{29} \\ Ir_{30} \end{bmatrix}$$

$$D(Project) = \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \vdots \\ D_{29} \\ D_{30} \\ D_{30} \end{bmatrix}$$

C_x^n = annual cost in year x of nth generation (\$/area); R^n = residual cost of nth generation (\$/area); Ir_x = implementation rate of year x (%/yr); D_x = discounting rate of year x.

In the annual cost K (UHRU) matrix, each member denotes the annual unit cost associated with a particular generation of GI implemented on a particular UHRU in a particular year. The annual cost matrix contains 31 rows, one for each year of the 30-year simulation and one for the RV. It also contains 30 columns, each representing the unit costs associated with a generation of GI (e.g. column 1 tabulates annual unit costs associated with GI installed in year 1; column 2 tabulates annual unit costs associated with GI installed in year 2; and so on). Superscripts denote the GI generation while subscripts refer to the year of the cost in which they were incurred (e.g. C_{25}^3 refers to the unit costs in year 25 of GI installed during year 3 of the simulation). The first C value in a given column of the matrix represents the unit IC, while the subsequent values normally represent the randomly generated unit O&M costs when useful life is long enough to end after the end of simulation. RV denotes the unit RV of the cost of a particular generation of GI at the end of the planning period.

Each of the I (Land Use) matrices contains only one column because the same implementation rate is used for all UHRUs in a given land use category. However, affected by construction delay, geotechnical investigation, and contracting issues etc., the rate of implementation is one of the uncertain factors considered to influence a GI project. Thus, each I matrix contains 30 rows, as new implementation rates are selected each year. Ir values represent either the adoption rate selected for each parcel UHRU in the land use for each year of the simulation or the repaving rate selected for each street UHRU in the land use category for each year of the simulation.

There is only one D (Project) matrix; the same inflation and interest conditions are assumed to affect all of the parcel and street UHRUs identically. However, this matrix has 31 rows; the final one is for discounting RV. The last two rows are identical since the discounting rate for RV is also referring to the whole planning period.

The overall NPV calculation for a single UHRU can be written as the following Equation (8) in which K is K (UHRU) matrix and D is D (Project) matrix, I is I (Land Use) matrix and A is the total area of a project.

$$NPV = \sum\nolimits_L^A (KI)^T D$$

$$= \sum A_L \left(\begin{bmatrix} C_1^1 & 0 & 0 & \dots & 0 \\ C_2^1 & C_2^2 & 0 & \dots & 0 \\ C_3^1 & C_3^2 & C_3^3 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ C_{30}^1 & C_{30}^2 & C_{30}^3 & \dots & C_{30}^{30} \\ -RV^1 & -RV^2 & -RV^3 & \dots & -RV^{30} \end{bmatrix} \begin{bmatrix} Ir_1 \\ Ir_2 \\ Ir_3 \\ \vdots \\ Ir_{29} \\ Ir_{30} \end{bmatrix} \right)^T \begin{bmatrix} D_1 \\ D_2 \\ D_3 \\ \vdots \\ D_{29} \\ D_{30} \\ D_{30} \end{bmatrix} \quad (8)$$

where A_L = area of land use L (acre or m^2).

CASE STUDY

We use LIDRA to compute the LCC of greening a two block-size watershed in NYC. This study area includes 24 individual parcels represented by the points in Figure 3 and a 227 m long street of 18.76 m width between parcel boards. The GI measures associated with each street and parcel type are also shown in the figure. Blue roofs and permeable pavement driveways are applied on the two big parcel properties; green roofs are assigned to the church parcel in the northeast corner of the study area; rain barrels are assigned to the town houses throughout the study area though combined with rain gardens and downspout disconnects in certain locations. The annual adoption and repaving rates are set at 33.3 and 10%, respectively.

Verification of LIDRA's LCC

Due to the lack of the LCC data of GI projects, this algorithm is difficult to validate on an individual local case

Figure 3 | Map of the sample watershed.

to check its accuracy of uncertainty. However, we are looking for opportunities to perform such a validation in our future work. In this section, the correctness of the LIDRA cost calculation will be verified with the use of an Excel spreadsheet. The average costs of GIs are used in this calculation; and the variance in LIDRA is removed. The average LCC calculated by Excel is provided in Figure 4. The left axis represents the annual cost of the proposed GIs during each year of the planning period. Each generation is represented by a different hatching style. In the first year, the whole column reads about $0.640 million which is entirely contributed by the IC associated with year 1 (e.g. the first generation). In the next year, the total annual cost is the combination of the second generation's IC and first generation's year 2 O&M cost. However, by the discounting effect, the total annual cost is slightly lower than the year 1 costs. In year 3, the total annual cost is almost equal to the IC of the third generation of GI plus the O&M costs of the first two generations, equal to approximately $0.635 million after discounting back to the present. Blue roof and rain barrel replacement costs kick in between year 21 and year 23, and are responsible for the increase in annual costs then. After the end of the planning period of 30 years, the RV of the three different generations (and their replacements) are summed up as a negative value. The curve (to be read on the right axis) depicts the cumulative program cost in PV. The PV of the LCC is approximately $2.92 million at the end of the 30th year. After subtracting the RV, the resulting NPV of the total program is approximately $2.72 million.

Using the same information, the results generated by LIDRA are shown in Figure 5. Note that to better compare the cost computations of LIDRA to the Excel results, a single implementation rate was used (not one derived from MC methods) for this presentation. Similar to the Excel results, the columns within the coordinate region represent annual program expenditures and are read on the left axis, while the curve is the cumulative cost and is to be read on the right axis; the column on the right side of the coordinate region represents the RV at the end of the planning period. Note that the columns in the coordinate region represent the total annual costs (e.g. the fraction that is implementation and not O&M are not shown). The computed annual program costs are identical to the spreadsheet results. The total costs of installation and O&M in the first three years for all generations are approximately $0.65 million per year; the crest of the reconstruction after 20 years discounted to around $0.09 million per year for three years; the total cost after 30 years climbs to about $2.9 million; and its NPV is $2.7 million.

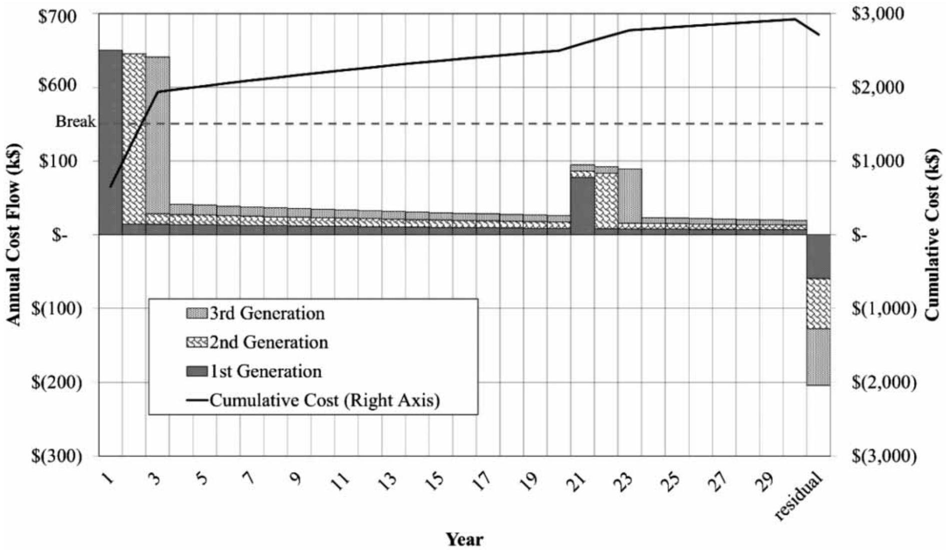

Figure 4 | Results from Excel algorithm.

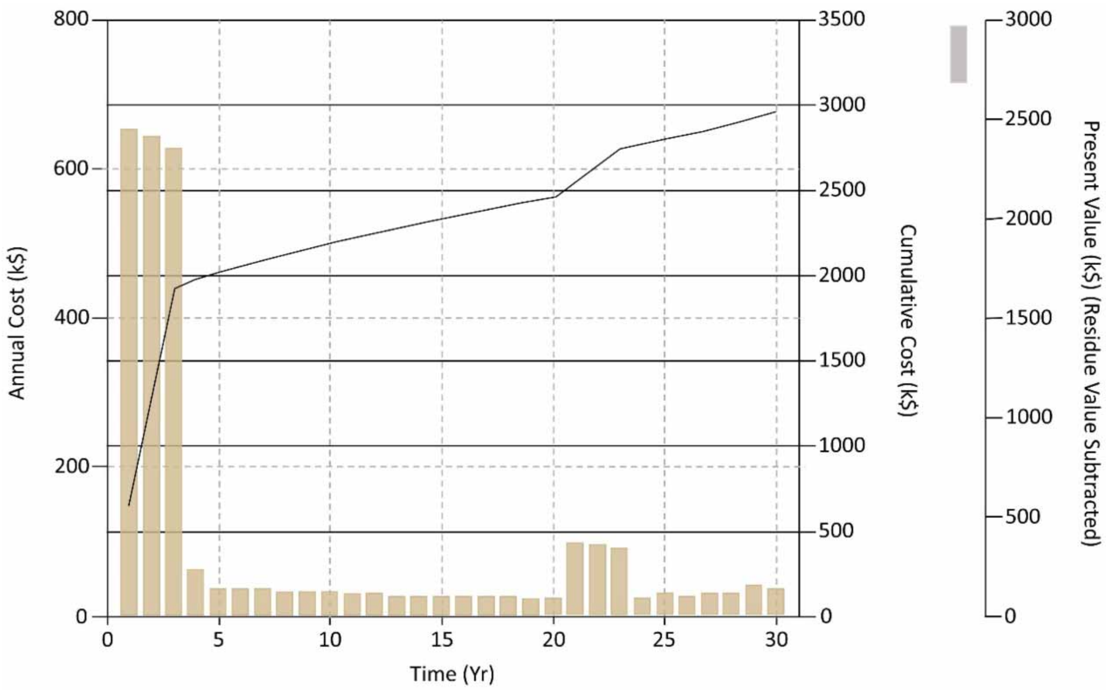

Figure 5 | Results from LIDRA.

Uncertainty effect in LIDRA's LCC

To visualize the extent to which socioeconomic uncertainty associated with GI implementation rates can influence the results, Figure 6 allows the adoption and repaving rates to vary using LIDRA's MC procedures. Boxplots are superimposed on the columns and the line used to designate the corresponding cost variations. The boxes indicate the interquartile range of the variation while the whiskers range from 5 to 95%. The bars and the curve represent the median values of 50 replications. Over the first three years of the simulation, the 90% confidence interval (e.g. 5–95%) of annual costs is from $0.55 million to $0.75 million. This variability is much greater than that computed for subsequent years, due to the greater uncertainty associated with GI construction (relative to O&M). The variance in the end of the planning period is expanded due to certain GIs reaching their minimum useful lives, such as street (25 years) and rain garden (25 years). Annual cost variation is discounted over time by macroeconomic parameters. All these variations are summed up on the cumulative cost. Although not recognizable due to different scale, the cumulative cost variation grows over time.

To further explore the effect of socioeconomic uncertainties on GI cost, a new simulation runs assuming a 10% implementation rate for all parcel and street UHRUs. The results are shown in Figure 7. Annual costs are higher during two different periods of the planning period: during the first ten years, when all of the GI sites are being initially populated, and during the last ten years, when certain GIs need a reconstruction (e.g. rain barrels, blue roof). In the first ten years, annual costs median grow from $0.19 million during the first year to $0.17 million during the tenth year (a relic of the stochastic variation of the implementation rate). The 90% confidence interval includes a ±$20,000 range, greater than annual expected program expenditures during other portions of the simulation. In year 21, some of the GI systems begin to require replacement. The peak annual program costs during this phase of the program begin at around $50,000 at year 21 and rise to $55,000 at year 30. This increase is mainly contributed by the reconstruction cost of other GIs reaching the lower end of useful life. The 90% confidence interval is ±$4,000 in year 21 and ±$20,000 in year 30. The O&M activities generate approximately $340,000 to $40,000 in annual costs during year 11 to

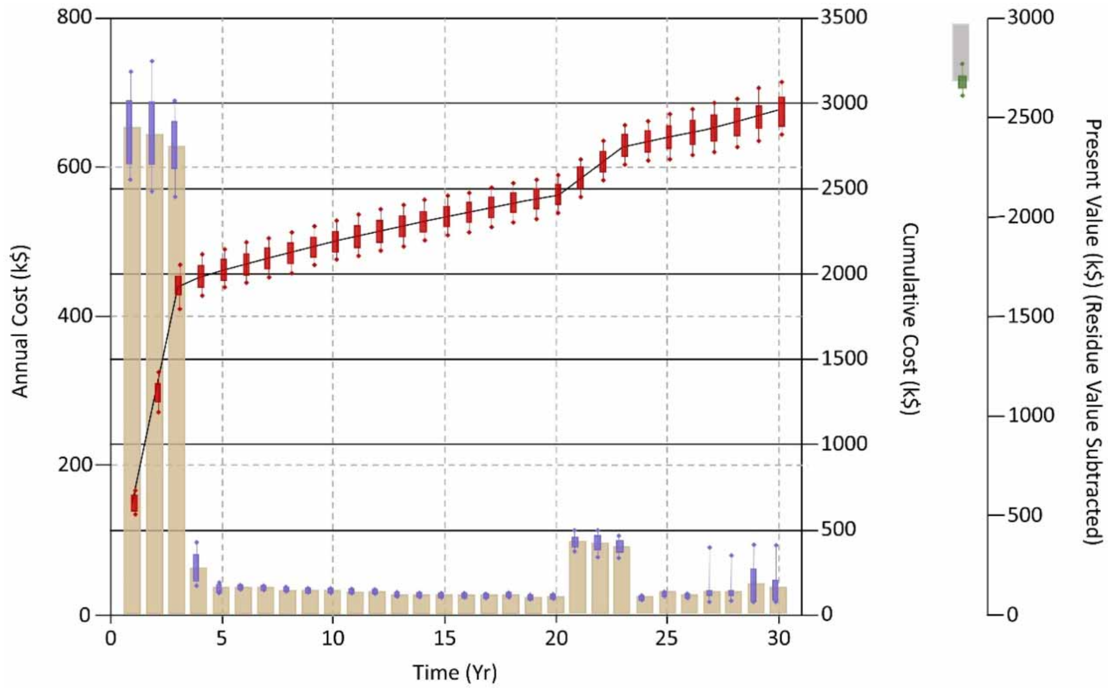

Figure 6 | Results from LIDRA with socioeconomic uncertainties of 33% implementation rate.

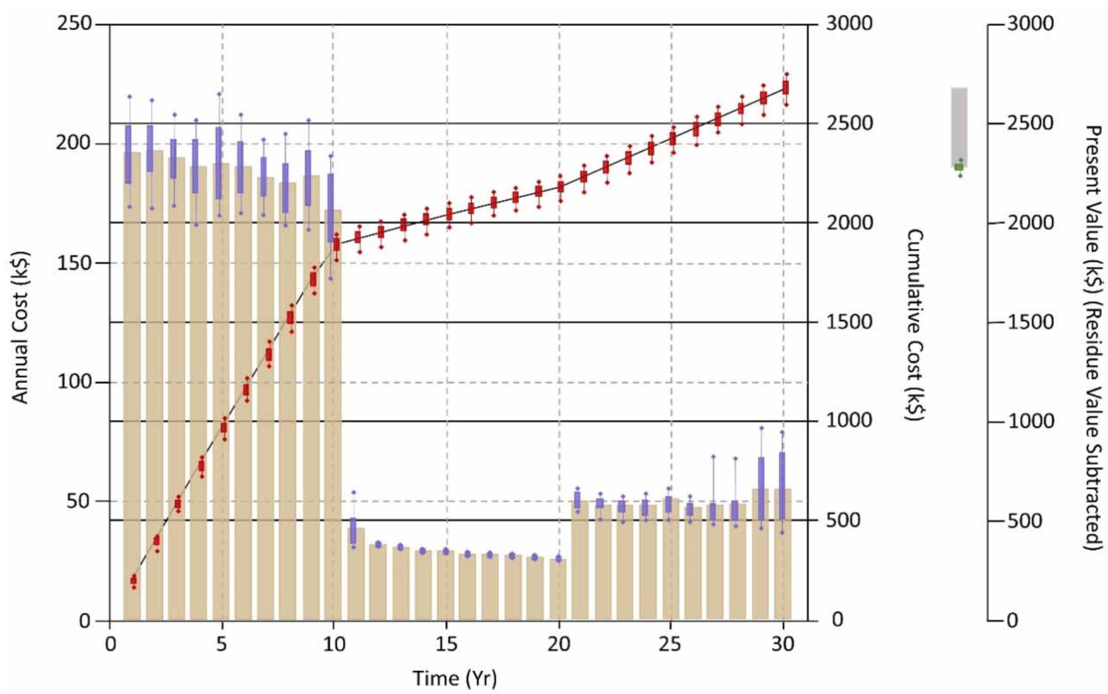

Figure 7 | Results from LIDRA with socioeconomic uncertainties of 10% implementation rate.

year 20, respectively, with relatively small variation. The RV of this simulation distributes over a relatively small range with a median around $0.5 million.

DISCUSSION AND CONCLUSIONS

The case study presented suggests that a GI LCC algorithm can be considered a useful tool to model the construction and the O&M of GI and assessing its uncertainties by integrating phased implementation, useful life switch reconstruction and MC. Phased implementation enables a model to mimic the construction speed in a real project. Implementation rate, which represents the speed of GI application, results in an alteration of the NPV of the GI investment throughout the planning period. When discounting future costs to a present day value, a slower implementation rate would appear to be more cost effective. However, by delaying implementation, the environmental benefits brought about by GI are also delayed. Project planners would ideally balance the two sets of considerations. (Yu *et al.* 2010). Reconstruction after useful life strengthens the cost algorithm by realistically considering the action of keeping a continuous GI function. When deciding what rate to implement GI, decision makers ought to consider that faster implementation may imply more required replacements later in the useful life, increasing the NPV of the total 30-year planning period. The MC model used in LIDRA quantifies various uncertainties, enhancing the portability of the model. For example, a GI program in New York City almost certainly will cost more than the same program in Cincinnati, OH because of geographical differences in labor, material costs and other factors. The upper bound of LIDRA's 90% confidence interval may be more suitable for use in New York, whereas users in Cincinnati may focus on the lower quartile results.

The LCC algorithm included in LIDRA can be used in conjunction with assessments of the socioeconomic uncertainty associated with implementation rate to provide ranges of expected costs for different types of GI programs. No such algorithm has previously been made available to GI modelers. Future work will allow non-linear implementation rates over the planning period. As time goes on, more data could be collected to compare and validate the algorithm's approach, accuracy and assumptions. Specifically, the long-term LCC data of a local scale project could help to validate the accuracy of the algorithm's results by checking if the project cost is within the range of the estimated uncertainty. The implementation phases of multiple projects could be used to validate if the linear implementation rate assumption is realistic or if the implementation uncertainty factor is practically important to be considered. Cost estimation from other budget calculation methods could be employed to compare with this algorithm's results. Both initial and O&M costs and useful lives for different GI types are also important to be updated by reviewing recent literature and projects.

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