INTEGRATED DESIGN WORKFLOW AND A NEW TOOL FOR URBAN RAINWATER MANAGEMENT

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ABSTRACT

For stormwater management, Low Impact Development (LID) practices provide more sustainable solutions than traditional piping and storm ponds. However, to be effective, LID practices must be integrated into planning at the beginning of the design process; yet architects and related design professionals making early decisions are not equipped to consider runoff calculations with their current tools. Responding to this dilemma, we have developed a rainwater runoff evaluation and management tool: Rainwater+. Designers will be able to connect this tool to their modeling or drawing software, and receive real-time feedback on the runoff volume of their design and any subsequent changes. Designers can thereby develop appropriate rainwater management strategies for the project based on local precipitation data, specific standards, site conditions and economic considerations. This paper introduces the method, interface and application of this new tool.

INTRODUCTION

With the advent of climate change, many regions in the world are experiencing heavier and more frequent rainfall (Dore, 2005). The subsequent flooding can cause significant property damage, even paralyzing sections of cities. The problem is exceptionally severe where massive, rapid urbanization is occurring (Huong, 2011). The conventional strategy—using piping to partially offset the environmental damage of impervious surfaces—is becoming obsolete because of its limited effect on drainage capacity and pollution control, as well as the high costs and disturbance to local neighborhoods (EPA, 2014).

As a result Low Impact Development (LID) practices are suggested as a viable solution (EPA, 2000) (Qin et al., 2013). LID practices increase sustainability by using porous pavement, bioretention, green roofs, rainwater harvesting, and other strategies that manage rainwater as close to its source as possible. These approaches increase groundwater replenishment, rainwater reuse, and on-site water balance, while mitigating downstream flooding (Pyke et al., 2011).

Unfortunately, design teams face a challenge when incorporating such LID strategies --namely, the traditional workflow for an architectural or urban design project considers site hydrology too late in the process. Typically in the U.S., rainwater runoff of a development project is calculated by hydraulic engineers who become involved during the Design Development phase or later. In the past, when conventional runoff management such as retention ponds or drainage pipes were the main solutions, the hydraulic engineer could calculate the required size of each system with minimal participation of the architect. However, because many LID practices must be integrated with other design elements, or to some extent, are parts of the design itself, architects and landscape architects must be able to develop preliminary onsite stormwater management strategies in harmony with early architectural, structural and landscape design. Addressing the problem later may limit one's options for selection, location, or sizing of systems.

Moreover, since local regulations, environmental standards such as LEED (USGBC, 2013), and design best practices increasingly mandate rainwater management targets, project teams need to consider runoff issues as an integrated part of the early design to guarantee the fulfillment of their goals. They should be able to conduct quick compliance checks, and if the design falls short, adjust their strategies accordingly.

Meanwhile, all of this should occur seamlessly within the fast-paced progression of early-stage design and without the need to stop momentum and switch software. In short, designers need a rainwater management tool, specifically one that integrates with their existing workflow and tools, that communicates how their design affects the site hydrology and allows them to test alternatives in real time.

Some hydrological engineers may fear the consequences of non-specialists conducting rainwater analysis themselves. However, architecture firms have already begun the trend of early in-house investigation within other specialties, such as energy simulation. Some energy modelers who later work with these firms argue that a more informed design team leads to more productive engagement in the project (Samuelson and Reinhart, 2012).

CURRENT TOOLS

Unfortunately, the existing tools available for rainwater management design do not fully support an integrated early-design process. The following sections describe some shortcomings with four of the popular tools.

Spreadsheet

A spreadsheet is the most widely used method for runoff calculations. However, populating the spreadsheet can be time-consuming and prone to input error, since the user must determine numerous inputs such as surface areas. Therefore, the spreadsheet is especially limiting for comparison of different design schemes or for calculations considering multiple storm events such as annual runoff volumes. Moreover, there is no interactive connection with the design. This leaves more complex determinations, such as rainwater flow-direction based on site topography, up to the user.

HydroCAD

HydroCAD, developed by HydroCAD Software Solutions LLC, is a hydrologic software for drainage projects. The interface is shown in Figure 1. Its function is limited to water conveyance and pond (including storage chamber) design, but it has no capacity for other runoff management practices such as green roofs, permeable pavement or rainwater harvesting.

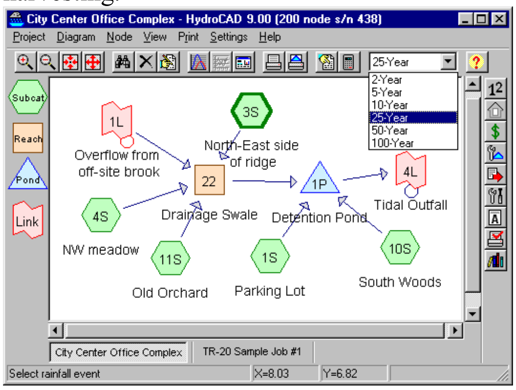

Figure 1 HydroCAD

National Stormwater Calculator

The U.S. Environmental Protection Agency's (EPA) National Stormwater Calculator, shown in Figure 2, is an application that estimates the annual amount of rainwater and frequency of runoff from a specific site. It is a "form filling" style software, which means it has no interconnection with the project's geometry. Instead of answering the question "how much green roof/permeable pavement etc. do I need to include in my design?" it requires users to assume the percentage of impervious area that will be treated by each LID practice. Therefore, designers trying to determine this input need a different kind of tool.

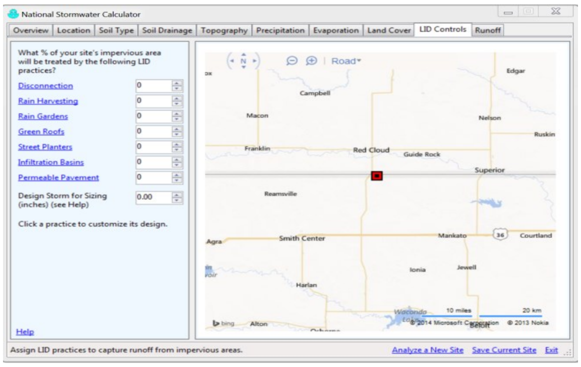

Figure 2 National Stormwater Calculator

Storm Water Management Model

The EPA's Storm Water Management Model (SWMM), shown in Figure 3, is a rainfall-runoff simulation model that predicts runoff quantity and quality from primarily urban areas. It is one of the most advanced software tools in runoff calculation, yet it still poses limitations for designers. First, there is no direct graphic interconnection with design software, which means the user needs to draw geometries in SWMM to represent each of the sub-catchment areas (or they must export simple geometries in CAD into a specifically formatted text file and then import the text file into SWMM). Second, since one simplifies the terrain into two-dimensional shapes, the software cannot tell users how runoff flows; instead, users need to develop a clear understanding of how to divide the terrain into sub-catchment areas, as well as the flow direction and convergence. A tool that could convey this information to users would be helpful to designers.

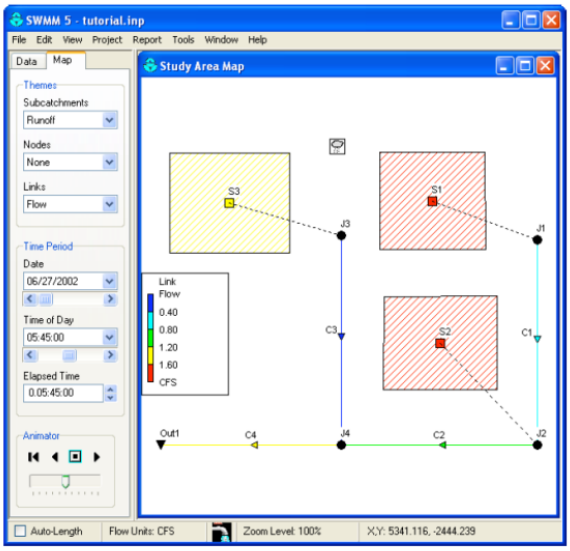

Figure 3 Storm Water Management Model

In summary, two major drawbacks are common in the current tools discussed above: 1. the lack of seamless and interconnected geometry input and 2. the lack of hydrodynamic analysis. Other minor issues includes 1. the software is not designed for LID and 2. insufficient support for quick system sizing and compliance check. Due to the nature of architectural and urban design process, a new tool that enables fast evaluation of dozens of design alternatives is in need. Such tool can be pragmatically adoptable and easily integrated into designers' decision making process.

RAINWATER+

Overview

To better serve architects, landscape architects, urban designers, and ultimately the hydrological engineers that work with them, we argue that the industry needs a designer-friendly urban rainwater evaluation and management tool that integrates into the early design process. To meet this need, we propose Rainwater+, intended to be an intuitive tool for designers to learn and use. It is a free, open source tool available by contacting the first author, or by download from the website rainwaterplus.com.

Platform

Rainwater+ is built upon the software platforms Rhinoceros and Grasshopper, developed by Robert McNeel & Associates. Rhinoceros is one of the fastest-growing, three-dimensional (3D) modeling tools for architects and urban designers. Because many designers already use Rhinoceros, Rainwater+ allows them to consider rainwater in their own model without interrupting their workflow to engage a separate tool.

Grasshopper is a graphical algorithm editor tightly integrated with Rhinoceros's 3D modeling tools. We chose this platform because of its popularity and, importantly, because Grasshopper made it feasible to create a designer-friendly, open-source tool, easily accessible and editable by users.

Using this platform, Rainwater+ is able to provide real-time feedback based on design models throughout the entire design process. Figure 4 shows the user's 3D model on the left alongside the Rainwater+ interface on the right, which is enlarged in Figure 5. The Rainwater+ outputs, shown in red, update in real time as the user adjusts either the 3D model or the Rainwater+ inputs.

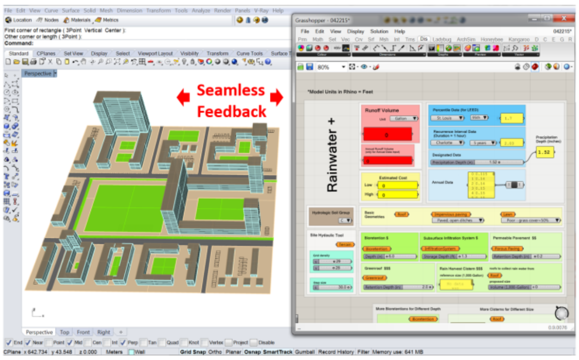

Figure 4 Integration of Rainwater+

Features of the tool

Rainwater+ can be used for design evaluation, comparison, compliance checking, and rough cost estimation. It has four major process components that will be discussed in more detail: 1. a built-in precipitation database, 2. a terrain analysis tool, 3. a runoff volume calculator, and 4. a library of LID practices and sizing components. The interface integrates directly with the designer's model in Rhinoceros. All components, except the terrain analysis tool, will also function with a two-dimensional drawing as well as a 3D model.

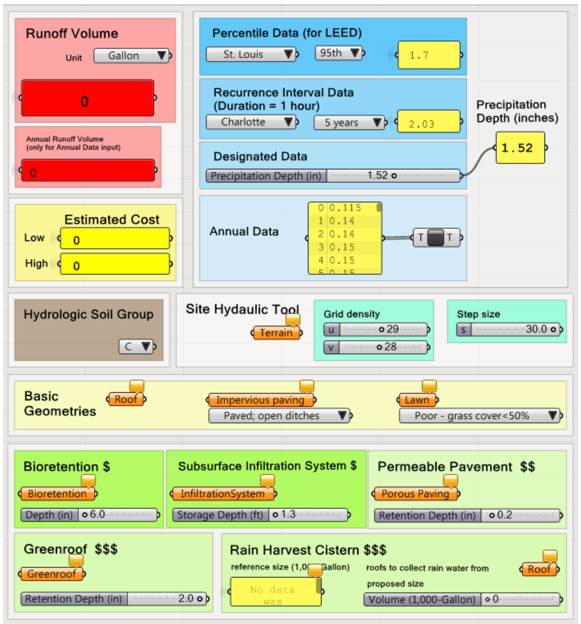

Figure 5 Interface of Rainwater+

A user's first step is to choose the site location, soil type, as well as precipitation data according to the goal or standard (such as LEED version 4) that the team aims to meet. The next step is to link model geometries in Rhinoceros into Rainwater+ components (roof, pavement or lawn) by clicking, or selecting by layer. After assigning cover characteristics (such as gravel or dirt for pavement), Rainwater+ will calculate the runoff volume of the current condition. The user then activates the terrain analysis tool to find the flow-converging areas. (A user can skip this step if the site topography will be redesigned). The last step is to interactively choose and design LID treatment areas, using Rainwater+ to help select and size the systems to achieve a specific runoff goal. The typical workflow is shown in Figure 6.

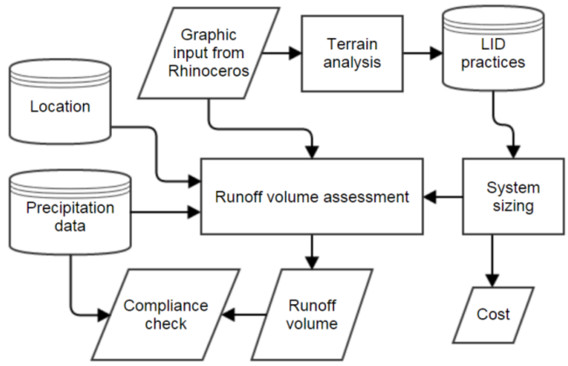

Figure 6 Workflow of Rainwater+

Rainwater+ has several distinct features as follows.

Precipitation Database

Users can choose from a library of multiple types of precipitation data input. Rainwater+ currently includes a library of percentile data input (85th, 90th, and 95th percentile rainfall event data for 16 major cities in the United States), as well as recurrence interval data inputs (once in 1,2,5,10,25,50,or 100 year rainfall events for 13 major cities in the United States). The precipitation data is downloaded from the National Oceanic and Atmospheric Administration (NOAA)'s Precipitation Frequency Data Server (PFDS). Users can alternately specify a custom rainfall depth for either a single event or for each event in a year.

Terrain Analysis Tool

The hydraulic tool in Rainwater+ can interpret a three-dimensional site plan to calculate the site's hydraulic flow conditions. This is realized by a simple iterative algorithm. First, a grid of nodes is projected onto the terrain surface. For each of the nodes, the algorithm finds the lowest point at one step size away from the original point. Then the node moves to the new point, and the process repeats. The density of the grid and the step size can be adjusted by the user.

The tool will illustrate the site's hydraulic conditions with red arrows. This feature allows users to visualize surface flow which helps them re-grade the site, if necessary, and place runoff mitigation systems, such as bioretention, in the most appropriate locations. Figure 7 shows an example site in the terrain analysis tool.

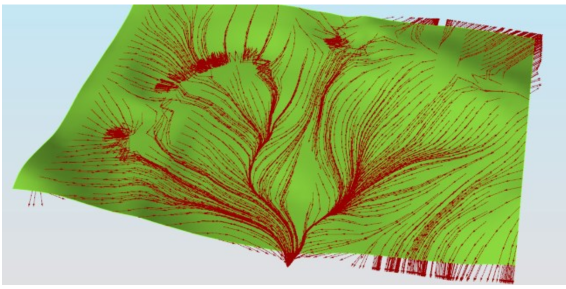

Figure 7 Terrain analysis tool

Library of LID Practices and Sizing Component

Rainwater+ can calculate the effects of various rainwater management strategies. The current LID library includes bioretention systems, subsurface infiltration systems, permeable pavements, green roofs, and rain harvest cisterns. First, the tool will calculate the runoff volume of the current conditions before any LID treatment is applied. Each surface in the model can be color-coded to show the equivalent runoff depth from that surface, as shown in Figure 8. Then in the LID design phase, Rainwater+ can help the user decide how much area the bioretention system, or subsurface infiltration system, should cover or how much storage capacity it should contain, based on site topology and runoff reduction targets. Once the user links the Rhinoceros model with Rainwater+, the runoff volume will be updated automatically in real time whenever the user changes the location, size or designed retention depth of the geometry, which helps users to quickly experiment and improve their design. The user can include one or more cisterns and bioretention systems on the site. The user then assigns the roofs, roads, or other surfaces from which the cistern or bioretention basin will collect the rainwater, and the tool suggests a reference depth or tank size that is large enough to contain the runoff. The topography tool can help the user with these assignments, by helping the user to visualize surface flow and redesign the site topography. Then the user can manually draw catchment boundaries and use this information when assigning surfaces to certain rainwater management systems. We plan to automate this process, by linking the results of the topography tool to the inputs of the runoff tool in future software versions.

Uses of the tool

Compliance Checking

Rainwater+ is able to perform compliance checks for LEED version 4 rainwater management standards, including both the percentile of rainfall events criterion (e.g. managing on-site the runoff for the 95th percentile rainfall events using LID and green infrastructure) and the natural land cover condition criterion (e.g. managing on-site the annual increase in runoff volume from the natural land cover condition to the post-developed condition). To check compliance for the first criterion, a user chooses the project location and precipitation data (e.g. 95th percentile rainfall events), applies LID practices next, sizes the systems, and then confirms that the runoff volume is less than or equal to zero. For the second criterion, the user runs the assessment for the natural land cover first, and then in the post-developed model, applies LID practices to reach runoff volumes that are the same as -or better than- before. The tool is also capable of checking state standards (EPA, 2011) that have quantifiable measures in forms of a percentile event, a particular event, a recurrence event, a percentage reduction or pre- and post- development comparison.

Preliminary Cost Considerations

Finally, Rainwater+ has a cost estimator component, which can roughly estimate the range of total cost of the designed LID practices. Cost data of Rainwater+ comes partially from the University of New Hampshire Stormwater Center 2012 Biennial Report (UNH, 2012), and partially from price quotes of industry-leading suppliers. We requested cost ranges for systems from two industry-leading suppliers in June 2014 and averaged the cost data from these three sources.

Calculations

In order to calculate runoff depth, the Natural Resource Conservation Service (NRCS) Curve Number method (Durrans, 2003) (U.S. DOA, 1986), developed by the U.S. Department of Agriculture (DOA), was selected for use in Rainwater+ among several available runoff calculating methods. This method was chosen because of its relatively complete database, as well as the fact that it has been widely used for decades. This method is shown as Equations 1, 2 and 3.

$$P_e = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{1}$$

Where:
P_e = depth of effective precipitation (runoff)
P = total rainfall depth in storm event
I_a= equivalent depth of initial abstractions
S = maximum possible water retention

Data analyzed by the NRCS indicated that on average $I_a = 0.2S$, thus the equation above becomes

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{2}$$

The maximum possible retention S is related to the Curve Number:

$$S = \frac{1000}{CN} - 10 \tag{3}$$

Where: CN = runoff curve number

The curve number used in Rainwater+, and shown in Table 1, is from Urban Hydrology for Small Watersheds TR-55 by the U.S. DOA (1986). In the Rainwater+ calculation, the curve number is automatically read from the table based on the land cover condition of each surface and user-specified soil type. Detailed land cover conditions are assigned to geometries (individual, group or layer) in the designer's model, which enables Rainwater+ to read geometry data from Rhinoceros.

Table 1 Curve Number

Cover description	Curve numbers for hydrologic soil group			
	A	B	C	D
Lawns Poor condition (grass cover < 50%)	68	79	86	89
Lawns Fair condition (grass cover 50% to 75%)	49	69	79	84
Lawns Good condition (grass cover > 75%)	39	61	74	80
Roofs	98	98	98	98
Paved parking lots	98	98	98	98
Paved (curbs and sewers)	98	98	98	98
Paved (open ditches)	83	89	92	93
Gravel	76	85	89	91
Dirt	72	82	87	89
Newly graded areas	77	86	91	94

Soils in the United States have been classifies by the NRCS into four hydrologic groups: A, B, C and D, as shown in Table 2. Group A soils have high infiltration rates. These soil types are available for selection by the user in Rainwater+. Hydrologic soil group for locations in the United States can be found on NRCS's SOILS website (soils.usda.gov).

Table 2 Hydrologic soil group

Type	Infiltration Rate	Texture
A	0.30-0.45 in/hr (0.76-1.14 cm/hr)	Sand and gravels
B	0.15-0.30 in/hr (0.38-0.76 cm/hr)	Coarse to moderately fine
C	0.05-0.15 in/hr (0.13-0.38 cm/hr)	Moderately fine to fine
D	<0.05 in/hr (<0.13 cm/hr)	Clays with high swelling, high water tables

As described above, the user's decision on the location of LID features is assisted by the terrain analysis tool, which will illustrate the flow and its convergence within the site boundary. The user's decision on the size of LID features is reached by adjusting the area and depth (or volume for cistern) of each feature to achieve the aimed runoff volume of the site. Table 3 lists the constraints of retention capacity of each LID feature adopted in Rainwater+, according to common engineering practice and manufacturer's catalog. These constraints are included in Rainwater+ to prevent unrealistic system sizing during the design process. However, users are able to override these settings with custom values if necessary.

Table 3 LID retention capacity constraints

LID	Constraint
Bio-retention	Preferred retention depth between 6 in and 12 in (max 15 in)
Subsurface infiltration system	Equivalent retention depth between 1 ft and 4.5 ft
Permeable pavement	Max retention depth 3 in
Green roof	Max retention depth 2 in
Rain harvest cistern	Max retention volume 50,000 gal

CASE STUDY

In this section, we demonstrate the use of Rainwater+ by conducting site evaluation and rainwater management design in the early design-phase of a real university campus extension plan in the U.S. Our goal with this case study is to prove that this site can be redesigned using low-impact development strategies to retain 95th percentile rainfall on-site and earn LEED version 4 Rainwater Management credits.

Preliminary Screening

The university's master plan depicts a development of more than a million square feet of new academic, research, and administrative facilities. The total area within the project boundary is approximately 178 acres (72 hectares). Given that the current site consists of a high percentage of previously-developed, impervious surfaces, there is an opportunity to reduce the volume of stormwater discharge to the river adjacent to the campus and increase water conservation by rainwater harvesting.

In Rainwater+, we chose the 95th percentile rainfall depth of 1.52 inches (3.86 cm) and Hydrologic soil group C from the software's built-in data library. Through the preliminary site screening test using Rainwater+, the visualized results, shown in Figure 8 suggest that building roof areas are the most problematic features, followed by the paved roads and walkways. The red and orange color of these areas illustrate that the largest portion of the 1.52 inches (3.86 cm) of rainfall falling on these surfaces will run off the site. In contrast, the lawn area in blue shows a partial infiltration capacity.

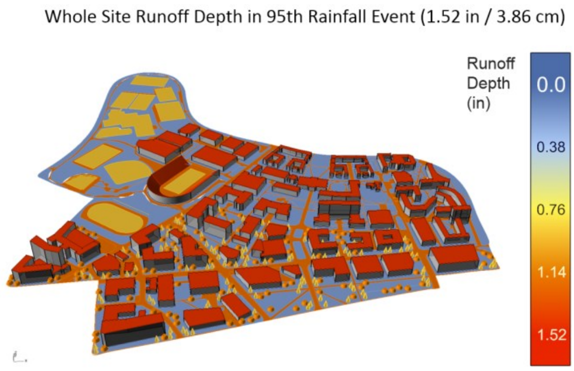

Figure 8 Preliminary site screen showing the Base Case design

Site Hydraulic Condition

The terrain of the CAD site model is two-dimensional, and site elevations attained from local government's GIS database show that overall the site is vastly flat, with very sparse contour lines ranging from 9 feet (2.7m) to 19 feet (5.8m) over several city blocks with no clear surface trend. Given this condition, we assume that the site drainage and flow direction will be redesigned, and the runoff will be channeled to the designated treatment areas. Therefore, we skip the Rainwater+ terrain analysis.

Rainwater Management

In order to better apply localized stormwater management practices, the proposed site has been divided into six sub-zones, as shown in Figure 9.

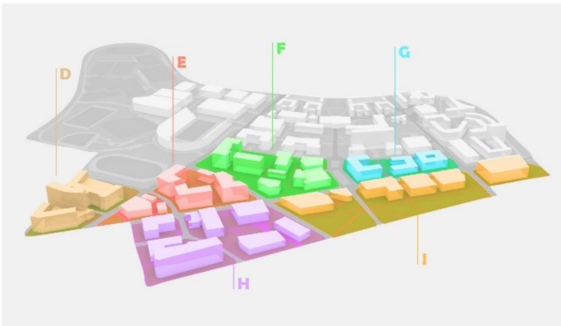

Figure 9 Subdivision of site

Next, we used Rainwater+ to test various rainwater management practices. For cost consideration, we selected bioretention practices first, because these systems generally have the lowest cost per unit of stormwater treated (EPA, 2014). Where we determined via experimentation with the design in the software that the bioretention system could not be designed to adequately capture the desired runoff volume, we considered permeable pavement, cisterns, and green roofs in that order based on their relative costs. In most cases a combination of practices were selected as part of an integrated treatment system. We repeatedly adjusted the system size of these design combinations by trial-and-error and checked the runoff number until it reached zero. The campus plans before and after redesign are shown in Figure 10. An example of the behind-the-scenes calculations performed by Rainwater+ for this case study are shown in Table 4.

Figure 10 before and after LID design

Table 4 Calculations - Zone D

Project Area D				
No LID				
	Area (sf)		Runoff Depth (in)	Runoff (gal)
Roof	130,203		1.30	105,503
Paved	42,057		0.82	21,440
Lawn	57,327		0.27	9,573
Total	229,587			**136,516**
With LID Planning				
	Area (sf)	Retention Capacity	Runoff Depth (in)	Runoff(gal)
Roof	26,041		1.30	21,101
Green roof	104,162	0.9 in	0.62	40,258
Porous Paving	42,057	2 in	-0.48	-12,584
Lawn	52,948		0.27	8,842
Bio-retention	4,379	8 in	-6.48	-17,689
Cistern		22,000 gal 18,000 gal		-40,000
Total	229,587			**-73**

The combination of bioretention, subsurface infiltration system and porous pavement were sufficient to retain the 95th percentile rainfall on site for a majority of the parcels. Other low-impact, onsite, stormwater management practices such as rain harvest tanks and green roofs were only needed in one zone where the percentage of impervious area was high.

Rainwater+ helped in the design and prioritization (based on approximate cost estimates) of the campus rainwater management strategies. The design and analysis performed here using Rainwater+ could be performed by anyone with a basic understanding of site topography, stormwater management, and the Rhinoceros modeling interface. In turn, their efforts could help reduce urban flooding and improve water quality.

Error Check

For error checking of Rainwater+, we used spreadsheets to recalculate site runoff by hand, using the NRCS curve number method. In this case study, the results have shown that discrepancies are below 0.2% between the spreadsheet and Rainwater+ results for both runoff evaluation and runoff reduction of LID onsite practices for all six zones, showing that the tool functions as intended.

LIMITATIONS

Rainwater+ is a tool for runoff volume assessment - the metric specified in most standards (both LEED and governmental). It has no bearing on rate estimation, peak calculation, and water quality prediction. Currently the annual rainwater runoff calculator does not consider the effects of concurrent rainfall events. Rainwater+ assumes that each catchment system is empty before receiving new rainfall. In future versions of the tool the drawdown time will be included in the calculations.

Costs are included for order of magnitude planning only. Users are encouraged to perform their own cost investigation and to confirm the availability and feasibility of the desired retention products and strategies. This tool is intended to aid in early design-phase investigation, where rainwater management may have been ignored otherwise. Rainwater+ is intended to enhance the dialogue with -rather than replace the involvement of- hydrological engineers or other specialists in the design process.

CONCLUSION

Rainwater management is no longer solely the engineer's responsibility in the new era of low-impact development. In fact, architects, landscape architects, and urban designers may be uniquely positioned to consider rainwater management strategies in early design, when they can integrate LID practices with other building and landscape design priorities. However, designers seldom consider rainwater performance in early design, and by the time a specialist becomes involved, many low-impact management opportunities may have been missed.

In any workflow, external consultants may take days or weeks to provide results. This feedback delay inherently limits the designer's ability to improve the design through repeated iteration and testing. However, no tool currently exists to adequately support designers in integrating rainwater performance into their early decision-making process.

Designers need a tool that can integrate seamlessly into their design workflow (and thus their native modeling tool) and provide real-time feedback on rainwater management performance. In addition to improving the design, a tool which provides real-time feedback may help designers to develop their own intuition for how their decisions impact rainwater performance for current and future projects. This early consideration of rainwater strategies could lead to more fruitful interactions with hydrological engineers later in the process and provide opportunities for these specialists to implement more sustainable strategies than if the designer had ignored these issues at the start.

Considering this context, Rainwater+ is intended to be an intuitive tool for runoff evaluation and management that can enable designers to integrate rainwater considerations into their design workflow. Rainwater+ has features tailored for designers: ease of use, real-time feedback, graphic interconnection, straightforward system sizing, compliance checking, and visualization of rainwater surface flow. We could find no currently available tool that contains all of these features or one that integrates into the designer's 3D model and design workflow.

We developed Rainwater+ with the intent to facilitate the integration of rainwater management strategies into the early design process, while increasing efficiency and accelerating the project's development.

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