An evaluation of the Stormwater-Footprint Calculator and the Hydrological Footprint Residence for communicating about sustainability in stormwater management

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Abstract

Low-Impact Development (LID) can enhance sustainability in stormwater management by attenuating excess runoff. Relevant technologies are typically implemented at individual lots and require the engagement of homeowners and developers. A new educational tool, the Stormwater Footprint Calculator (SFC), was developed to improve knowledge and change attitudes and behavior regarding stormwater sustainability. Similar to online carbon-footprint calculators, the SFC synthesizes a participant's answers about lot-level and neighborhood land use and calculates hypothetical effects on in-stream flows, using hydrologic simulation. Participants receive feedback about their stormwater footprint using a new metric, the Hydrologic Footprint Residence (HFR), which measures the effect of urbanization on stream flow based on the duration and extent of flooding. An experiment was fielded to test the SFC as

a tool for communicating about sustainable stormwater management and to compare the HFR against an orthodox stormwater metric, peak flow. A convenience sample of undergraduate students ($N = 510$) participated in the experiment. The results indicate that completing the SFC improved knowledge about the causes of stormwater runoff and LID technologies (though not about the effects of stormwater, which was already high), and it influenced intention to support sustainable stormwater management. The results also indicate that HFR provides a viable alternative to conventional engineering metrics for communicating a stormwater footprint and shows the value of online calculators for communicating complex civil engineering concepts.

Introduction

The construction of new buildings, infrastructure, and public utilities for urbanization alters landscapes and converts natural land cover to impervious areas. These areas, in turn, generate large volumes of stormwater runoff that directly affect receiving bodies of water by causing flooding, erosion, and degradation of in-stream ecosystem habitats (Leopold, 1968; Richter et al. 1996; Roesner et al. 2001; USEPA, 2004a;b). Centralized infrastructure, such as detention ponds, may be constructed to manage increased runoff through storing and slowly releasing large volumes of water. Detention ponds, however, have limited capabilities in restoring comprehensive natural flow regimes and require valuable land (McCuen, 1979; Roesner, et al. 2001). Low Impact Development (LID) is an alternative stormwater management strategy that allows rainwater to infiltrate the ground closer to where it falls and may improve local hydrology (USEPA, 2000).

The LID technologies, such as green roofs, rainwater harvesting, permeable pavements, and rain gardens, are typically designed for decentralized placement at individual lots or neighborhoods. They reduce runoff by increasing infiltration and flow paths at the source of

generation, such as parking lots, buildings, roadways, and sidewalks. Because LIDs must be implemented close to these individual infrastructure components, they are typically placed on private properties or within neighborhoods. Because they are decentralized and distributed at many locations throughout a community, a large number of individual citizens or neighborhood organizations may be actively involved in their implementation. Local utilities, therefore, rely on public engagement and property owners to bear the costs (Keeley, 2007).

To encourage the adoption of LID technologies, policy makers, planners, and builders need outreach tools that will inform and educate the public (Keeley, 2007). Communities may benefit from cost savings that emerge from decentralized management. Implementation of LID technologies at the lot or neighborhood level can reduce expenses that a community must pay through taxes or service fees to maintain, update, and replace extensive centralized infrastructure. The adoption and performance of decentralized infrastructure systems, however, depends on public participation in small infrastructure development (Rojanamon et al. 2012), and low awareness and resistance to change among the general public can impede sustainable stormwater management (Roy et al. 2008). Local stormwater utilities have had only limited success in motivating homeowners to install stormwater technologies on individual lots (Marsalek & Chocat, 2002; Thurston et al. 2003; Braden & Johnston, 2004; Thurston, 2006). These techniques are controversial and may require new initiatives by utilities and by local governments because they deviate from the conventional approach to stormwater management, which uses an end-of-pipe centralized design (Coffman et al. 1999; USEPA, 2000). Although some site-specific LID projects have been successfully implemented and monitored in the United States, for example in Philadelphia (Landers, 2009), Chicago (Dreher, 2009), and the Woodlands

(near Houston) (Yang & Li, 2010), lot-level LID technologies have not gained widespread adoption in the United States or abroad (Ahiablame et al. 2012; Roy et al. 2008).

A necessary step in improving public acceptance of LID is to raise awareness of threats to stormwater sustainability by educating citizens about the risks of urbanization and the potential benefits of using LID approaches (Dietz et al. 2002; Prokopy et al. 2009; Shaw et al. 2011). However, communicating this information involves complex scientific and engineering concepts. To convey the importance of individual decisions on flooding and the sustainability of local water bodies to lay audiences, this research developed and tested a new educational tool, the Stormwater Footprint Calculator (SFC). The SFC was designed to provide individualized information while engaging participants by asking them to reflect on their own choices. It uses participants' feedback to a set of questions about their local landscape (e.g., information about the characteristics of their residence and neighborhood) to simulate the effects of development decisions on the health of water resources, which is quantified as the Stormwater Footprint. The SFC uses engineering data and hydrologic simulations and explains complex scientific and engineering concepts throughout the participatory process. In-stream conditions resulting from new land-use changes are compared to predevelopment conditions and to development scenarios that use lot-level LID technologies.

Research has provided tentative evidence of the value of computational calculators and footprint calculators in other contexts (Franz & Papyrakis, 2011; Gottlieb et al., 2012; Gram-Hanssen & Christensen, 2012). These tools are designed for communicating complex concepts and used to educate and raise awareness, which may in turn change behavior. Previous work has depended on focus groups, interviews, and literature reviews to generate insights about the effectiveness of online-footprint calculators. These studies have found that including viable and

realistic options in calculators may increase their effectiveness, and that a footprint calculator can encourage new perspectives for thinking about complex environmental issues. These studies provide valuable insights about the potential utility of such tools, but research is also needed that explores the causal relationships between completing a footprint calculator and the resulting changes in knowledge, attitudes, and behavior. The work presented here fills such a need by testing the influence of participation in the SFC on changes in knowledge about stormwater management, attitudes about sustainability in the context of stormwater management, and intentions to engage in and advocate for sustainable stormwater management.

The research presented here describes experiments to evaluate the SFC, and through these experiments, a newly developed metric is compared with a conventional metric for calculating stormwater effects. Information about hypothetical changes in flows and flooded areas in a receiving water body based on participants' choices are displayed using the Hydrologic Footprint Residence (HFR). The HFR measures the effects of stormwater runoff based on the area and duration of flooded land as a storm wave passes through a stream channel. The experimental design tested the efficacy of this new metric against an orthodox metric, peak flow. The results demonstrate that participation in the SFC (1) increases knowledge about stormwater management related to LID technologies, (2) influences participants' attitudes about environmental concerns in development (though not as expected), and (3) increases the likelihood that participants report that they intend to take action to support sustainable stormwater management. The results also demonstrate the efficacy of the HFR for communicating about stormwater sustainability. The remainder of the paper is organized as follows. The Background section describes the relevant research that has explored stormwater management as a sociotechnical system, public participation in stormwater management, and the

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use of online footprint calculators for increasing environmental awareness. The Stormwater Footprint Calculator Section describes the engineering model and questionnaire that are included in the SFC. The section also describes the tests that were conducted to determine the communicative efficacy of the SFC and the HFR. The Results Section presents hypotheses that were supported through experimental results. Finally, the Conclusion Section discusses the implications and limitations of the research.

Background

A Sociotechnical Perspective for Stormwater Management

Urban stormwater management is a sociotechnical system, in which social and technical aspects cannot be managed separately (Geels 2005; 2007), and the interactions between the two distinct systems can significantly affect the performance of stormwater sewers (Cettner et al. 2012). Urban planners and designers generally depend on community acceptance, funding, and behavior modifications to implement best strategies, whereas the community is dependent on planners and engineers to identify feasible and cost-effective designs. Conventional approaches to stormwater management rely almost solely on technical or infrastructure improvements; new approaches, however, consider a combined sociotechnical approach that incorporates public education and behavioral changes in addition to centralized infrastructure (Geldof, 2001).

Social impacts on urban drainage arise, in part, due to the potential stormwater savings that can be attained through nonstructural best management practices and lot-level decentralized source control. Source controls are minor measures implemented individually at the lot level, and LID technologies include, for example, enhanced rooftop detention, flow restrictions at catch basins to enhance local storage and detention, reduced lot grading to slow down runoff flow and enhance infiltration, and stormwater harvesting and reuse (Marsalek & Chocat, 2002).

In general, homeowners may be reluctant to implement lot-level LID technologies, as they may not see the need to pay for stormwater management. For example, stormwater fees are often seen as a "rain tax," and citizens perceive that they are paying for infrastructure twice. Citizens perceive that they first pays taxes to build infrastructure and, secondly, pay stormwater fees to use the infrastructure (Kaspersen, 2000). Similarly, citizens may be reluctant to invest in lot-level LIDs, when they have already paid municipal taxes to support stormwater infrastructure. Site-specific information about the contribution of an individual lot to system-wide stormwater volumes could serve as a powerful public information tool to give all members of a community a stake in watershed management. The impacts of further urbanization on stormwater volumes can be calculated through the use of engineering models and may be used to better motivate individual investments to protect nearby surface and groundwater systems (Keeley, 2007).

Decentralized stormwater-source control should be studied and planned within its social context, as cultural and social relationships can drive the success of introducing new technologies (Pahl-Wostl, 2007). Along with developing the technology and infrastructure to implement innovative stormwater-source control, new knowledge and attitudes must be created within the community for progressive adaptation to the changing dynamics of sociotechnical systems (Smith & Stirling, 2010). Educational approaches are needed to merge technical and social processes and involve the community in the stormwater-management design process (Geldof, 2001).

Increasing Public Participation in Stormwater Management through Educational Outreach

Research on community outreach to improve stormwater management has demonstrated that improving knowledge and changing attitudes is difficult. For example, Swann (1999) found that television, radio, and local newspapers are among the more effective tools for improving the ability of participants to recall a stormwater message, whereas brochures and handouts are among the least effective; however, even intensive efforts may not bring about desired behavioral changes. Taylor et al. (2007) describes an educational outreach program designed to improve knowledge about the effects of stormwater runoff and littering on water quality. Educational campaigns included displaying posters in shop windows, stormwater-drain stenciling, and distributing brochures, and the research evaluates improvements in knowledge, attitudes, and behaviors within the community. The campaign had mixed results, as evaluated through surveys and interviews, observations of behavior, self-reports, and stormwater quality monitoring. The campaign was not successful at making significant and sustained improvement in the knowledge of and attitude of community members towards littering and litter-management strategies. It was modestly successful at changing behaviors and reducing litter loads to the adjacent stream. A similar study in Connecticut reported modest behavior changes and slight improvements in water quality based on an educational campaign (Dietz et al. 2002).

Footprint Calculators for Educating about Sustainability

A footprint is a measure of the quantity of resources required or consumed to support a lifestyle. For example, the ecological footprint is a measure of human demands on the earth's ecosystems and represents the amount of land and sea area needed to produce the resources that a population consumes (Rees, 1992; Wackernagel & Rees, 1996). Two footprints have been developed to evaluate water-use behaviors and practices. Hoekstra & Chapagain (2007) define

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the "water footprint" as the total volume of freshwater that is used to produce the goods consumed in a country or a region. The "water-supply footprint" calculates the catchment area that generates the water supply upstream of a community to estimate the amount of water that can be sustainably allocated for human demands (Stoeglehner et al. 2011). The term "stormwater footprint" has been used in informal settings to refer to the effect of an individual lot on runoff, such as the area of impervious surface in a lot, the volume of water that a rainwater cistern can capture, or the nutrients that would be discharged into a receiving water body, but has not been given a measurable definition in the literature (e.g., Little River Watershed Association, 2009; Rahim & ClimateWire, 2012; Winnipesaukee Gateway, 2012).

As footprints are designed to communicate about the sustainability of their resource use, footprint calculators have been developed to make this information accessible and understandable (Franz & Papyrakis, 2011; Mozner & Csutora 2013). A footprint calculator asks participants to answer questions about their behaviors, habits, home characteristics, and community characteristics that are relevant to resource consumption. They receive feedback about how their own consumption affects the local or global environment. The ecological footprint, for example, can be calculated as the resources required for supporting the annual lifestyle decisions of an individual in terms of food, housing, energy use, transportation, and so forth. One way to communicate the footprint is the number of planet Earths that would be required to support the individual's lifestyle if the entire global population adopted the same lifestyle. An ecological footprint calculator makes these determinations based on the participant's responses to questions about his or her lifestyle and provides immediate feedback about environmental consequences (Pacheco et al. 2006; Moos et al. 2006; Ohl et al. 2008; Baldo et al. 2009; Kim & Neff, 2009; Berners-Lee et al. 2011; Mozner & Csutora 2013).

For example, Franz & Papyrakis (2011) conducted a qualitative assessment of footprint calculators. They argue that these metrics can act as a powerful signal if they are designed to illustrate the difference among alternative choices and their interconnection to aggregate environmental impacts. Gram-Hanssen & Christensen (2012) evaluate an online footprint calculator through analysis of focus-group data. They report that the footprint calculator can be an important "interlocutor," or agent of conversation, to qualify and inspire users to reflect on complicated issues rather than only communicating facts about behavior and climate change. Gottlieb et al. (2012) found that the ecological footprint enabled high school students to understand and evaluate the connection between personal lifestyle and the impact on ecological systems that support life on the global level.

The Stormwater Footprint Calculator

The Stormwater Footprint

The Stormwater Footprint is defined here to quantify the stormwater impacts that would occur if all residents in a watershed made similar land-use and landscaping decisions. The Stormwater Footprint is quantified as the stormwater runoff, in response to a specific rainstorm, that would occur if all land within a watershed were converted to the same land use and land cover. To calculate a value for the Stormwater Footprint, land-use parameters are applied for the entire area of a hypothetical watershed, and the stormwater impacts are simulated for a *design storm*, which has a certain depth and intensity of precipitation based on the statistical properties of historic rainfall patterns. Design storms correspond to the frequency with which they occur. For example, a five-year design storm is defined by the depth of rain that falls over a certain duration (such as a 24-hour period), and that depth is exceeded, on average, once every five

years. The experiment compared two metrics used to indicate the stormwater footprint: peak flow and the Hydrologic Footprint Residence (HFR). The peak flow is the highest value of the volumetric flow rate of water in a receiving surface water body, such as a stream or river. The HFR is the total area of land within the channel and floodplain of a receiving surface water body that is inundated for one hour as a result of a design storm.

Stormwater Footprint Calculator Design

The SFC determines the land-use specifications in a participant's neighborhood through a set of sequential questions. The tool uses a participant's responses to create land use-input conditions for hydrologic simulation and returns an associated stormwater impact or footprint. Participants receive values for the Stormwater Footprint corresponding to conditions before urban development, conditions that reflect their land-use decisions and conditions that reflect the implementation of LID technologies including permeable pavements, rain-harvesting systems, and green roofs, which are simulated as retrofits to the participant's land-use decisions.

The SFC intersperses educational content before and after the questions to explain stormwater-management concepts. It introduces and describes a set of ideas related to stormwater runoff encompassing: 1) the environmental impacts including increased flooding, ecosystem degradation, and introduction of pollutants due to increased stormwater runoff; 2) the increase in runoff as a response to increased urbanization; and 3) the importance of land-cover choices on stormwater-runoff volumes. Exemplary LID technologies are also described following a set of related questions to highlight the connection between the benefits of these technologies and the participants' own lot-level decisions. For example, the questions about local lot-level landscaping are followed by a description of rain gardens and their benefits. The SFC

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was developed for multiple platforms to enable the widest range of users; it therefore includes an online Flash application and an iPhone/iPad application[1]. Figure 1 shows a screenshot of the first page, and Figure 2 shows screenshots of each of the questions. Figure 3 provides an example of the numerical results that a participant could receive. Participants also received information after each of their choices that describe a corresponding LID technology that could be used at their residence. For example, after participants indicate the type of parking lot at their apartment complex, a description of permeable pavements is provided. It was assumed that the majority of the participants would not have LID technologies at their homes before taking the quiz.
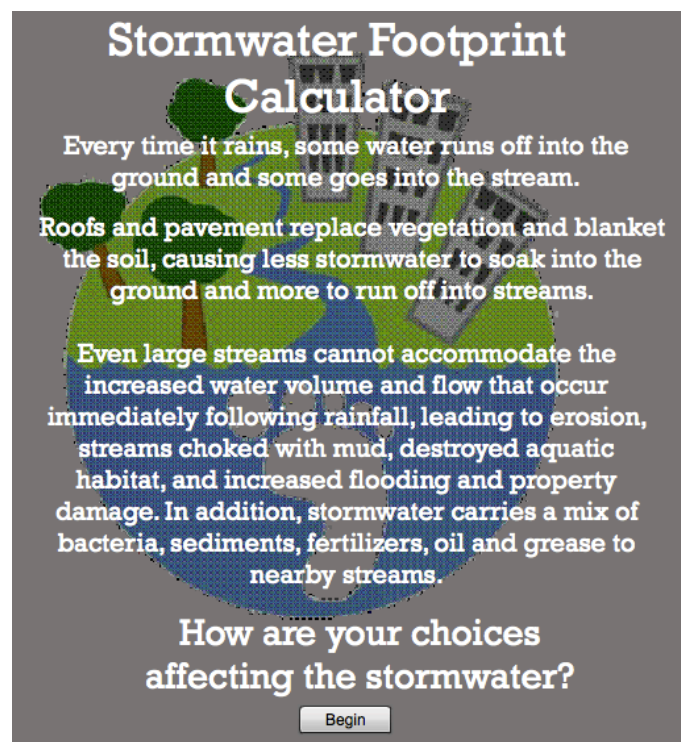
Figure 1 Screenshot of the first page of the Stormwater Footprint Calculator.[1]

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[1] The version of the SFC that provides feedback using the HFR can be found at http://www.macromorphic.com/HFRQ/Calculator/HFR.swf.

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Figure 2 Screenshots of the SFC questions. Answers have been selected to represent those of a

participant who lives in an apartment.
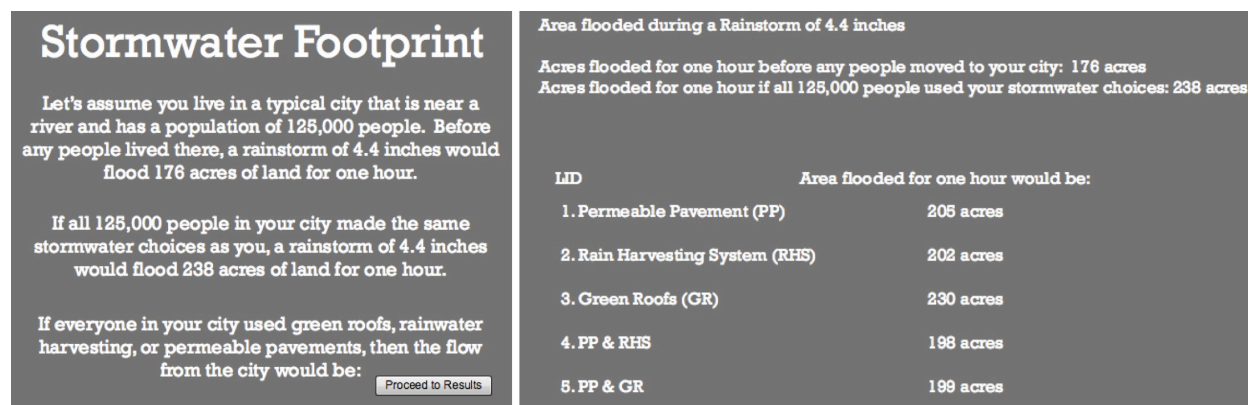
Figure 3 Screenshot of the results for a set of SFC answers, using HFR for feedback. Answers

have been selected to represent those of a player who lives in an apartment.

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Hydrologic Simulation

Engineering data and stormwater science were integral in building the SFC to create realistic stormwater conditions that could occur due to participants' land-use and landscaping decisions. Participants in the SFC receive feedback based on calculations using engineering data for an illustrative watershed, the Harris Gully sub-basin, located in Brays Bayou in Houston, Texas. The Harris County Flood Control District has made available the data that describe the watershed (Harris County Flood Control District, 2010), and the SFC uses an engineering model that converts rainfall into streamflow values using hydrologic calculations (USACE, 2008). The SFC uses participants' responses to questions to calculate input parameters for the engineering model and simulate land-use conditions. Five LID scenarios were created and modeled: permeable pavement, rainwater harvesting, green roofs, permeable pavements in combination with rainwater harvesting, and permeable pavements in combination with green roofs.

The engineering model calculates peak flow, which is the highest volumetric rate of streamflow resulting from a rainstorm, and also calculates the HFR. The HFR was developed as an alternative metric to the peak flow for evaluating the magnitude and timing of streamflow resulting from a rainstorm. The HFR translates the in-stream flow rates into an area of flooded land that is inundated for one hour, which may be more accessible and familiar to a layperson for comprehending changes or impact due to anthropogenic effects. It may also provide a metric that represents environmental impacts more accurately than changes to the peak flow, as it can represent comprehensive changes to the time series of streamflow, rather than only instantaneous peak-flow values. The HFR is a single value that represents the area of land that is inundated due to a flood wave that passes through a pre-defined section of a stream and the duration of the inundation. The HFR is measured in units of area-time, such as acre-hours (ac-hrs), and can be

expressed as the total amount of land that is inundated for one hour for a design storm. Giacomoni et al. (2012) describe HFR in further detail and demonstrate a set of example HFR calculations for a small watershed.

Table 2 summarizes the quiz questions and the effects that answers have on the hydrologic calculations. When a participant selects a house or apartment in response to the first question, the entire watershed is populated with a low- or high-development density, respectively, through the use of a computer simulation, to represent that all residents of the community select the same lifestyle, with respect to their stormwater impacts. For the watershed that is used in the SFC, the population size is 80,000 if houses are used as the dwelling unit, and 125,000 for apartments. The higher density that accompanies apartments produces an increase in the stormwater footprint, compared to results that are produced when a participant selects a house. Because the amount of land, rather than the number of people, is kept constant in the simulations, populating the entire watershed with apartments creates a more impervious land cover, compared to lots that use landscaping. A participant's choices for all questions are used to calculate land-use parameters that serve as inputs to the engineering model. Scott (2011) and Politte (2011) provide detailed descriptions of the equations used to translate participants' answers to meaningful parameters in the hydrologic simulation.

Table 2 Stormwater Footprint Calculator questions, answer alternatives, and effects on
participant feedback

Calculator Questions	Answer Alternatives and Effects in Feedback
Choose housing type	House - Decreases HFR
	Apartment - Increases HFR
Do you have a yard?	Yes - Decreases HFR
	No - Increases HFR
Do you have a garden and/or landscaping?	Yes - Decreases HFR
	No - Increases HFR
[If housing type=house] Do you have a driveway?	Yes - Increases HFR
	No - Decreases HFR

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[If yes] Are the driveways shared?	Yes - Decreases HFR No - Increases HFR
Do you have a parking lot?	Yes - Increases HFR No - Decreases HFR
[If yes] Do you have an assigned spot?	Yes - Increases HFR No - Decreases HFR
Do you have a sidewalk?	Yes - Increases HFR No - Decreases HFR
[If yes] Are there sidewalks on both sides of the street?	Yes - Increases HFR No - Decreases HFR
[If no] Are there sidewalks on the opposite side of the street?	Yes - Increases HFR No - Decreases HFR
Choose street width	Wide - Increases HFR Narrow - Decreases HFR
Do you have green space in your neighborhood or apartment complex	Parks & Trails - Decreases HFR Neighborhood Landscaping - Decreases HFR Both - Decreases HFR None – No effect

Note The effect on the calculations (increased or decreased HFR) provides only a rough approximation. Additional detail about the ways choices influenced the results, including the equations used, is available upon request from the corresponding author. It is also available in Scott (2011) and Politte (2011).

Testing the Communicative Efficacy of the SFC and the HFR

The first set of hypotheses focuses on the effects of completing the SFC on knowledge, attitudes, and behavioral intentions. First and foremost, participation was expected to improve knowledge about stormwater management and LID technologies. We hypothesized that,

H1a: Completing the SFC will improve participants' knowledge about stormwater management.

H1b: Completing the SFC will improve participants' knowledge about LID technologies.

Although the SFC was designed as a tool for disseminating information about stormwater management, we also hypothesized that completing it would influence participants' perceptions of the relative importance of environmental and economic concerns in development. We expected that completing the SFC would encourage participants to see environmental concerns as relatively more important compared with their prior beliefs. In other words, participation

should encourage attitudes that reflect the importance of sustainable development over economic imperatives. We hypothesized that,

> H2: After completing the SFC, participants will report more support for environmental concerns in development over economic concerns.

The principal promise of tools such as the SFC is not only knowledge and attitude change, but also behavioral change. We hypothesized that,

> H3: After completing the SFC, participants will report that they are more likely to take action to support sustainable stormwater management.

Although evaluating the causal links between actual behavior and participation in an online calculator goes beyond the scope of this study, it was possible instead to assess the influence of participation on self-reported behavioral intentions. The causes of actual behavior in the real world are multiple and complex. Previous research has established, however, that behavioral intention provides an imperfect but reasonable proxy for actual behavior (Kim & Hunter, 1993; Kollmuss & Agyeman, 2002; O'Keefe, 2002; Wallace et al., 2005); however, that we are measuring the behavioral intentions is an important limitation that should encourage caution in interpretation of results (see the discussion of this issue below). We expected participants to report an increased willingness to take a variety of actions in support of sustainable stormwater management.

The second set of hypotheses posited that the metric used to communicate the influence of personal decisions would also affect participants' knowledge, attitudes, and behavioral intentions. Specifically, we expected that participants would more readily interpret and understand feedback when stormwater impacts were communicated using HFR. First, we hypothesized that,

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H4: SFC participation feedback utilizing HFR will have a greater effect on participants' knowledge about stormwater management and LID technologies than conventional stormwater metrics.

Likewise, because the HFR results are more easily understood, the HFR version of the SFC should have a greater influence on attitudes and behavioral intentions than the peak-flow version. We therefore hypothesized that,

H5: After completing the HFR version of the SFC, participants will report more support for environmental concerns in development over economic concerns than participants who completed the peak-flow version.

H6: After completing the HFR version of the SFC, participants will report that they are more likely to take action to support sustainable stormwater management than participants who completed the peak flow version.

Experimental Evaluation of SFC and HFR

To test these hypotheses, a Solomon four-group experimental design was implemented consisting of four conditions. The first and second condition provided feedback using the HFR and the third and fourth conditions used peak flow. The first and third conditions included a pretest questionnaire to measure change in knowledge and attitudes and the second and fourth conditions did not control for the effects of such a pre-test questionaire (if any). After completing informed consent, each participant was randomly assigned to one of the four conditions. All participants completed a version of the SFC followed by a post-test questionnaire and demographic questions.

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Measures

For this study, we developed indices for assessing participants' knowledge, attitudes, and behavioral intentions. Participants' knowledge about stormwater management was assessed using three measures. The first, the knowledge of stormwater effects (KSE) index consisted of five statements: Stormwater can cause 1) flooding, 2) erosion, 3) damages to property, 4) loss of health of aquatic species, and 5) discoloration of tap water. The second index, the knowledge of stormwater causes (KSC) index, included the following statements: Excess volumes of stormwater can be caused by 1) new parks, 2) rainwater harvesting, 3) new buildings, 4) new green space, 5) new parking lots, and 6) green roofs. The participants evaluated each statement as true or false. Values for KSE and KSC indices were calculated by averaging each participant's proportion of correct responses. They ranged from 0 (none correct) to 1.0 (all correct). The KSE and KSC indices were used to assess hypotheses 1a, which focused on improvements to knowledge about stormwater management generally.

Hypothesis 1b focused specifically on knowledge about LID technologies. The third index, the Development Knowledge (DK) index, assessed participants' ability to evaluate the effects of seven development choices on stormwater: 1) wide sidewalks, 2) shared driveways, 3) permeable pavement, 4) rainwater harvesting, 5) green roofs, 6) narrow streets, and 7) new parking lots. Participants could respond in one of four ways: increases flooding, decreases flooding, no change, or I don't know. The DK was calculated as the average of a participant's correct choices (+1) and incorrect choices (–1). The value for the DK index ranges from –1.0 to 1.0. All knowledge indexes were found satisfactorily reliable using Cronbach's α, which measures the internal consistency of the items (Cronbach's $\alpha_{KSE} = 0.62$, $\alpha_{KSC} = 0.77$, $\alpha_{DK} = 0.65$). In general, values greater than 0.60 are acceptable.

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Attitudes about the relative importance of environmental and economic issues in development were measured using the environment and economics (EE) index, also developed for this study. It consists of three statements: 1) In my neighborhood, the growth of new businesses is more important than having green space, 2) Environmental protection reduces economic development, and 3) Private property rights must always trump conservation efforts.

Participants' intention to take action to support sustainable stormwater management was assessed using the willingness to take action (ACTION) index. It consists of seven statements: 1) I am likely to tell my friends about low-impact development; 2) I am likely to vote for political candidates who support low-impact development; 3) I will tell my coworkers about how low-impact development can help our community; 4) I am likely to install rain-capture devices at my home; 5) I am likely to install a green roof at my home; 6) I am likely to try to use some flooding-friendly technology at my home; and 7) I am likely to advocate with my local government for flooding-friendly technologies. Participants rated the statements in the EE and ACTION indexes using a 6-point, Likert-type scale (1 = strongly disagree, 2 = disagree, 3 = somewhat disagree, 4 = somewhat agree, 5 = agree, and 6 = strongly agree). Responses were averaged across items for analysis, and both indexes were satisfactorily reliable (Cronbach's $\alpha_{ACTION} = 0.91$, Cronbach's $\alpha_{EE} = 0.65$).

Sample

A convenience sample of participants ($N = 510$) was recruited at a large state university in the southeastern region of the United States through undergraduate-level classes in liberal arts and engineering courses. Students were offered extra credit (not exceeding 1% of their overall course grade), but were also offered an alternative means of earning the credit if they elected not

to participate to avoid coercing participation. Power analysis, a statistical technique for determining sample size, indicated that the recruitment target for the entire experiment should be approximately 460 participants (or 115 per condition). Recruitment exceeded that target.

Results

The participants included undergraduate students in over thirty different majors from every college at the university and provided variability in the knowledge base of participants (Table 1). Most participants (78.6%) were not in majors affiliated with engineering. Students in engineering majors did not demonstrate a greater magnitude of change in the knowledge or attitude indexes (KSE, KSC, DK, EE), but they did report a somewhat smaller but still positive change in their willingness to support sustainable stormwater management than students in other majors (an increase of 0.29 on average for engineering students versus a 0.59 increase for other majors; $t_{ACTION} = 6.732, df = 225, p < 0.001, r = 0.19$). However, the experimental design accounted for that difference by including a similar mix of participants in each condition through random assignment. Comparison of majors with more math or science coursework versus other majors yielded no significant differences on the changes in the variables under study. Likewise, participants' own self-reports of their previous experience with the engineering concepts under study were not significantly related to the variables under study. As reported in Table 1, participants were more likely to be female (60.5%), and most were third-year students (35.4%). Most participants described themselves as white (81.0%), followed by Latino/a (9.3%), Asian-American (3.4%), and African-American (2.8%). Participants ranged in age from 18 to 59 ($M = 21.06, SD = 2.18$). A summary of the analysis employed to test hypotheses is presented in Table 2, and the analysis is described in detail below.

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Table 1 Demographics of participants

Characteristic	Percentage of Participants
Gender	
Female	60.5%
Male	39.5%
Year of study	
First	11.0%
Second	35.0%
Third	35.4%
Fourth	18.1%
Graduate	0.4%
Ethnicity	
White	81%
Latino/a	9.3%
Asian-American	3.4%
African-American	2.8%
Major	
Communication	30.39%
Civil, aerospace, chemical, and electrical engineering	21.37%
Business and management	11.96%
General studies	10.39%
Others, including economics, history, mathematics, political science, psychology	9.81%
Accounting and finance	5.29%
Health and nursing	3.33%
Biology	3.14%
Kinesiology	2.75%
Education	1.57%

Table 2 Summary of results

Measures	a	t	df	r (effect)
Δ Knowledge of Stormwater Effects (KSE)	0.62	0.461	230	-
Δ Knowledge of Stormwater Causes (KSC)	0.77	6.732*	225	0.23 (medium)
Δ Development Knowledge (DK)	0.65	10.466*	230	0.33 (strong)
Δ Willingness to take action (ACTION)	0.91	11.873*	220	0.29 (strong)
Δ Environment and economics (EE)	0.65	-2.297*	219	0.08 (small)
KSE for HFR vs. PF	-	1.312	506	-
KSC for HFR vs. PF	-	1.442	502	-
DK for HFR vs. PF	-	2.791*	506	0.12 (small)
ACTION for HFR vs. PF	-	0.800*	497	-
EE for HFR vs. PF	-	-0.107*	496	-

Note * $p < .05$. Δ refers to the change in these measures between the pre- and post-tests. HFR refers to Hydrological stormwater residence. PF refers to peak flow.

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Analysis for Hypothesis Testing

Knowledge, attitude, and behavioral intentions. Paired-samples t-tests were used to assess changes in participants' knowledge, attitudes, and behavioral intentions by comparing the difference between pre- and post-test results. Hypothesis 1a, that completing the SFC will improve participants' knowledge about stormwater management, received partial support. Participants' knowledge about the effects of stormwater ($t_{KSE} = 0.461, df = 230, p = 0.645$) was not improved by completing the SFC beyond what might be expected due to chance. Scores for the KSE questions improved from 92.6% to 93.2%, suggesting that participation did not have much influence on knowledge about the effects of stormwater beyond existing high levels of knowledge. However, participants' knowledge about the causes of stormwater runoff did improve ($t_{KSC} = 6.732, df = 225, p < .001$). The KSC scores increased from 67.1% to 79.2%, supporting hypothesis 1b, that completing the SFC will improve participants' knowledge about LID technologies. Participants' knowledge about the effects of different development options did improve ($t_{DK} = 10.466, df = 230, p < .001$). The DK scores improved from 0.17 to 0.46.

To provide a sense of the power of these effects, we report *r*, a metric used in the social sciences to indicate the correlation between variables of interest that allows researchers to evaluate and compare the magnitude of effects. This measure ranges from –1 to +1, and rules of thumb for social science effects categorize effects as small ($r \approx 0.10$), medium ($r \approx 0.20$), and large ($r \approx 0.30$) (Cohen, 1988). The effect of participation on knowledge of the causes of stormwater was medium ($r_{KSC} = 0.23$), and the effect of participation on knowledge of development technologies was strong ($r_{DK} = 0.33$). These results indicate that completing the calculator did affect participants' knowledge about stormwater management, though not for all indexes.

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Hypothesis 2, that participants will report more support for environmental concerns in development over economic concerns after completing the SFC, was rejected. Participants' attitudes about the relative importance and commensurability of economic and environmental interests in development changed in an unexpected direction. Participants were actually somewhat more likely to respond that economic development and environmental protection are not incommensurate after completing the SFC ($t_{EE} = -2.297, df = 219, p = 0.023$), though the effect was small ($r_{EE} = 0.08$). Participants may have inferred through playing the SFC that environmental protection and economic growths are not necessarily conflicting goals, but can be achieved simultaneously.

Hypothesis 3, that participants will report that they are more likely to take action to support sustainable stormwater management after completing the SFC, was supported. Though the measure is only an indicator of behavioral intention that did not include, for example, a concrete sense of the costs of LID technologies, the results did indicate that participants were more likely to report a willingness to take a variety of actions to support sustainable stormwater management ($t_{ACTION} = 9.579, df = 217, p < 0.001, r = 0.23$).

These results of the test of hypotheses 2 may indicate that, after completing the calculator, participants saw these technologies as a way to accommodate economic interests in development without sacrificing environmental concerns. It is our supposition that participants may have dismissed any tradeoff between environmental protection and economic development. Future research might investigate if teaching individuals about LID technologies could encourage them to see development and environmental protection as commensurate. Completing the SFC did have a robust and expected effect on participants' willingness to take action to support more sustainable stormwater management.

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Comparing the HFR and peak flow for communicating the effects of development on stormwater.

Independent samples t-tests were used to test the second set of hypotheses. These analyses compared the results on the post-test questionnaires between the HFR and peak-flow conditions. Hypothesis 4, that SFC participation feedback utilizing the HFR will have a greater effect on participants' knowledge about stormwater management and LID technologies than the peak flow, received partial support. Participants receiving HFR feedback were not more likely than those receiving peak-flow feedback to have higher knowledge scores about the causes (t_{KSC} = 1.442, df = 504, p = 0.150) or effects (t_{KSE} = 1.312, df = 506, p = 0.190) of stormwater. Although scores were higher for the HFR participants, the differences were not larger than would be expected due to chance. Participants receiving HFR feedback were more likely to have higher knowledge scores about the effects of flooding of different development alternatives (t_{DK} = 2.791, df = 506, p = 0.005). It was a reliable but small effect (r_{DK} = 0.12).

Hypothesis 5, that after completing the HFR version of the SFC participants will report more support for environmental concerns in development over economic concerns than participants who completed the peak flow version, was not supported. There was no difference between the two groups (t_{EE} = –0.107, df = 496, p = 0.915).

Hypothesis 6, that after completing the HFR version of the SFC, participants will report that they are more likely to take action to support sustainable stormwater management than participants who completed the peak-flow version, was also not supported. There were no differences in participants' willingness to take action to support more sustainable stormwater management (t_{ACTION} = 0.574, df = 492, p = 0.566).

That communicating using the HFR mattered only for development alternatives but not for the other measures of knowledge, support for environmental issues above economic issues, or willingness to take action, may stem from the design of the SFC. Participants' exposure to the metrics occurred at the end of the calculator when their choices, including the presence or absence of low-impact development technologies, were scored using either HFR feedback or peak-flow feedback (Figure 3 demonstrates a set of example SFC results using the HFR for feedback). In other words, the metrics were used mainly to frame differences in the alternate, hypothetical states of development. Neither tool was used to communicate the causes or effects of stormwater per se. The small but reliable difference in knowledge about LID technologies is promising in that receiving HFR feedback may have been easier to understand. Receiving HFR feedback performed as well as receiving peak-flow feedback for all indices that were measured and outperformed peak-flow feedback for the DK index. Therefore, the results offer tentative support for the HFR as a more easily accessible metric than peak flow.

Conclusion

The SFC was developed as an educational tool that could influence the effects of personal land-use decisions on stormwater sustainability. It was designed to extrapolate personal decisions to an entire population to calculate the level of resource consumption for stormwater runoff. At the same time, this evaluation of the SFC demonstrates the utility of testing such educational tools not only to evaluate their efficacy but also the relative merits of engineering metrics for communicating to lay audiences.

Completing the SFC did improve knowledge about the causes of stormwater runoff and LID technologies, but not about the effects of stormwater, which was already high. The

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improvement in knowledge scores offered promising support for the educational utility of tools such as the SFC. A better understanding of the knowledge base of an intended audience could inform more targeted messaging and allow more focused use of this tool: communicating the effects of land-use decisions and sustainable alternatives on stormwater management.

Completing the SFC also influenced attitude change regarding the relative importance of economic and environmental interests; however, the direction of the change was not consistent with our expectations. In fact, participants were more likely to see economic interests commensurate with environmental interests. This result may highlight a problem in the way that attitudes about the environment and the economy were conceptualized and operationalized in the assessment of the SFC. Previous research has demonstrated public discourse regarding environmental issues frames sustainable environmental practices and economic prosperity as mutually exclusive in ways that are counterproductive and not necessarily accurate (Wade-Benzoni et al. 2002). Members of the public may frame these issues as a choice between the environment and the economy. We hypothesized that completing the SFC would shift participants' understanding, where understanding the consequences of stormwater management would improve attitudes about the importance of environmental protection over economic interests. In that way, our design reified the false dichotomy that the participants may have rejected in part due to their completion of the SFC (although that is only supposition). The results indicate that, in fact, participation does not make people think the environment is more important. Instead, it may reinforce the idea that environmental protection and economic growth are not necessarily conflicting goals, but can be achieved simultaneously. In future research, we can rework the EE index to allow for a direct test of the potential of the SFC and tools like it for

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correcting the misconception that development means a choice between environmental protection and economic prosperity.

The results also indicate that completing the SFC could increase an indicator, albeit self-reported, of participants' intention to support the development of stormwater technologies. The nature of research means that no one study is without flaws, and that the design only measures behavioral intention and not actual behavior is a limitation of this study. Although behavioral intention has in previous research been demonstrated to be a robust predictor of actual behavior, the link is nonetheless not absolute (see in particular the literature on the so-called value-gap, Kollmuss & Agyeman, 2002). The strength of the relationship is likely affected by the degree to which the behavior was volitional (i.e., versus behaviors that are habitual or difficult to change, Wallace, et al., 2005) and the measures of behavioral intention reflected the actual behaviors of interest (Kim & Hunter, 1993). The ACTION index does at least reflect the range of behaviors of interest, and implementing and advocating for sustainable stormwater practices is volitional to some degree.

However, actual behavior is far more complex and involves considering factors not included in the SFC. For example, the SFC does not attempt to educate about the relative costs of development alternatives. Costs that a homeowner must bear may impede the adoption of LID technologies; however, as their use becomes more widespread and the installation of these technologies becomes more common and efficient, the costs of LID should decrease (USEPA 2007). In this study, cost, however, is a factor that might limit the degree to which the choice to actually implement LID technologies is volitional. Likewise, research has indicated that the stability of the relationship between intention and behavior degrades over time (O'Keefe, 2002). The ACTION index specified behaviors in an amorphous future. Despite these limitations, the

results still provide evidence that tools like the SFC may encourage sustainable behavior. Similar to other footprint calculators (e.g., van Dooren & Bosschaert 2013), the SFC may be most effective as part of a holistic educational campaign to improve awareness and change behaviors.

The sample used is another limitation that should encourage caution in interpreting the results. The aim of this study was a controlled, experimental evaluation of the SFC and stormwater metrics, and the convenience sample of students served that end. However, the particular composition of the sample likely limits the degree to which the results are generalizable to other audiences. Students, as argued above, may not have had to consider the decisions that are part of building, buying, or maintaining a home. These individuals may thus be less likely to participate in the governance of their local utility. However, students do make at least some decisions about where to live, what policies deserve their attention and support, and for whom they should vote. Tools like the SFC might inform those decisions, specifically for a long-term planning horizon and as part of a comprehensive educational campaign. Likewise, the students' lack of previous knowledge about some aspects of sustainable stormwater management means that their responses may provide a useful indicator of lay audiences; however, even college students who have not yet graduated have received more education than large proportions of the general public. The results do nonetheless offer tentative evidence that can guide the development of tools such as the SFC, and they provide a warrant for investing in research to test the effects of footprints and footprint calculators on other audiences.

A hydrologic modeling system was used to calculate changes to the peak flow, which is a conventional engineering metric of watershed health, and the HFR, a newly developed stormwater footprint. HFR was recently introduced to indicate more holistically the influences of urbanization on the downstream residences and changes to the flow regime as the area of land

inundated for one unit of time in response to one rainfall event. The HFR did not uniformly outperform the peak-flow metric; it did enhance participants' understanding of the effects of LID technologies on stormwater. At the same time, it did not perform more poorly in any of the comparisons despite ample power in the design to find even small differences. The results provide tentative evidence that the HFR may be more effective than the peak-flow metric in some cases.

The study overall provides support for the efficacy of footprint calculators for communicating complex scientific and engineering concepts to lay audiences. The SFC, through the use of engineering models and simulation data and the comparison of different stormwater metrics, is also a tool for civil engineering research. Future investigation might build on the lessons of this study to develop even more engaging computational platforms to provide more dynamic and iterative feedback about different development technologies. Dynamic and iterative games can enhance the fidelity of feedback that proved useful in these data. Likewise, the efficacy of the design has demonstrated that such games might allow scientists to test concepts in engineering. The results should prove especially promising for managers of civil engineering infrastructure who need tools that can support and encourage social and technical transitions from a conventional urban water infrastructure system to a more sustainable regime.

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