Title: Low Impact Development in Chicago for Integrated Watershed Management Across Scales

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Problem and Research Objectives:

Proliferation of impervious surfaces in most watersheds is a serious problem resulting in negative ecological effects on receiving bodies of water and an increased risk of flooding frequency and magnitude. In urban areas where significant portions of the sewer network are combined sanitary and storm sewers, the problem of combined sewer overflows (CSOs) is a serious source of water pollution, both upstream and downstream of sewage treatment plants (Thurston, 2006). Urban development dramatically increases impervious surface area in most watersheds, preventing water infiltration and promoting direct surface runoff. This extensively modifies hydrologic processes in the watershed, resulting in less evapotranspiration, greater peak flows and flooding, enhanced erosion, limited groundwater recharge, increased loads on wastewater treatment plants in combined-sewer-overflow (CSO) systems, and reduced quality of receiving surface water bodies, (NRC, 2008; USEPA, 2007). In response to the increased magnitude and frequency of stormwater runoff events, municipalities and local governments seek cost-effective strategies to manage the risks associated with these stormwater flows (Parikh, 2005). In order to determine the best management strategies, research needs to be done to elucidate the mechanisms underlying different stormwater management strategies at the site and watershed scales and proper valuation of their ancillary benefits.

Between 1982 and 1997, approximately 25 million acres were developed in the United States, representing a 34 percent increase in the area of developed land, with only a 15 percent increase in the population during the same period (USDA, 2001; U.S. Census, 2000). As such, stormwater is one of the leading sources of pollution of all water bodies in the United States (USEPA, 2007). Of special concern in the Great Lakes region are the effects of CSO systems on water quality. There are almost 200 communities in the Great Lakes basin with CSO systems, discharging more than 40 billion gallons of diluted sewage into the Great Lakes annually (Chicago Tribune, 2011; NWF, 2010). Each year, this directly impairs biological ecosystems (NRC, 2008), results in many hundreds of beach closures (NRDC, 2007), and has sickened up to 12% of swimmers at one Lake Michigan beach (NRDC, 2007). According to the USEPA's (2008) Clean Watersheds Needs Survey 2008 Report to Congress, the nation needs to invest at least $298 billion in its aging sewers, $187.8 billion for wastewater treatment and collection systems, $63.6 billion for combined sewer overflow corrections, and $42.3 billion for stormwater management, all in the face of decreasing resources. Billions of dollars are being invested in tunnels in cities across the country to capture CSOs (e.g., Chicago, $3.7 billion, MWRDGC, 2013; St. Louis, $2.7 billion, STLMSD, 2011; Washington DC, $2.6 billion, DCWater, 2010). However, as determined by city planners for the city of Chicago, tunnel systems alone may not be sufficient to prevent flooding and CSO discharges (Chicago Tribune, 2011).

Over the past 20 years, state and local governments have concentrated their efforts on implementing conventional stormwater management practices to address storm water runoff and

CSOs, with a focus on controlling peak flow rates and suspended solids concentrations, typically at the neighborhood level, and often without a comprehensive watershed plan that considers cumulative hydrologic effects (USEPA, 2007). A dramatic shift in thinking has occurred over the past five years, where state and local governments are starting to embrace Low Impact Development (LID) practices, with the goal of maintaining or closely replicating predevelopment hydrology. LID practices promote stormwater infiltration, filtration, evapotranspiration, and on-site storage through a variety of small-scale technologies that, when integrated throughout a watershed, can holistically address shortcomings associated with and/or complement conventional stormwater management. Notable examples of these practices are rain gardens, green roofs, porous landscaped detention systems, permeable pavements, and grass swales. Recently, requirements to include LID stormwater practices have been incorporated into the *Long Term Control Plan (LTCP) Consent Decrees* for several cities. For example, St. Louis will include $100 million of LID in their LTCP and Chicago and Washington DC will incorporate LID in their LTCPs (UIM, 2012, DCWater, 2012).

A lack of knowledge on the performance of LID and their impact on downstream waters, perceived higher costs, and regulatory hurdles have been major impediments to their adoption (NRC, 2008). The USEPA (2007) developed 17 case studies of sites that implemented LID practices, and identified capital costs savings between 15 to 80 percent for all but one site (USEPA, 2007). The USEPA also documented environmental (e.g., reduced runoff volumes and pollutant loadings to downstream waters, and reduced incidences of combined sewer overflows) benefits, but these were not quantified. LID encompasses a wide range of practice with different local- and watershed-scale impacts, different technical constraints, and different costs and benefits. Lack of technical details, such as the watershed-scale performance, can influence and bias the decision-making process when selecting appropriate systems (Vivattene and Ellis, 2013).

This project focuses on quantifying the hydrologic and economic performance of LID intervention in a watershed for managing stormwater by using the village of Dolton, IL, as a case study. The objectives of this project are to: 1) improve our understanding of the hydrologic behavior of green roofs, 2) understand the impact of green roofs on hydrological processes at the watershed scale, 3) examine the watershed-scale impact of different spatial distributions of GRs, and 4) explore the economies of scale and benefits of scaling green roofs in a watershed. We choose green roofs because we have access to a unique data set and a process-based model (HYDRUS-1D) for this LID. We choose the Chicago area because we recently developed a watershed model for the Chicago metropolitan area in cooperation with MWRDGC, the City of Chicago, and CH2M Hill.

Methodology

Three major tasks have been identified to achieve the above objectives.

Task 1 – 100% Complete

Collect and use high-resolution meteorological data to predict the outflow hydrographs for a "representative and scalable" green roof. Since 2008, a 260 m^2 extensive green roof (GR), located at the Business Instructional Facility (BIF) at the University of Illinois, has been monitored and modeled. Immediately adjacent to and one story above the green roof is a 60 m^2 conventional roof (CR), that was also monitored. A suite of sensors installed on the green roof monitors incoming and reflected solar radiation, relative humidity, wind speed, rainfall rate, and runoff rate. Undisturbed samples of the green roof soil matrix were taken from two locations and analyzed by New Mix Laboratory for particle size and bulk density. Hydrus 1D (Simunek et al., 2009) was used to simulate the water flow through the BIF green roof. Hydrus was chosen because it has been demonstrated to accurately model variably-saturated water flow through a green roof soil matrix (Hilten et al. 2008; Palla et al. 2009). Water flow was simulated in one dimension (i.e., 1D) because of the relative homogeneity of the green roof soil profile and lack of a topological gradient (i.e. no lateral subsurface flow). Continuous high-resolution (1-minute) rainfall and runoff data along with meteorological conditions and physical properties of the engineered soil were used to calibrate and verify the Hydrus-1D model, taking into account inter-event processes (i.e., drying and evapotranspiration, ET).

Task 2 – 75% Complete

Incorporate the green roof response into a watershed model for Dolton, IL, to test the effect of different scenarios such as percent coverage and variable densities at different locations

The Illinois Urban Hydrologic Model (IUHM) is a probabilistically based approach that is a marked departure from traditional deterministic models used to simulate urban sewer systems (Cantone and Schmidt, 2011). IUHM was modified to incorporate small-scale LID - specifically green roofs (GR), to effectively and correctly evaluate the effects of green roofs on the hydrologic response of urban catchments, giving full consideration to scaling, heterogeneity, and thresholds. Using the modified IUHM, we explored the effect of green roof implementation in the CDS-51 catchment. We examined different rainfall scenarios including hypothetical design storms, low-intensity, long duration events, high-intensity, short duration events, and long-term precipitation records. We varied percent coverage of impervious roof area by GRs and placement of GRs in different areas of the watershed to determine the sensitivity and threshold of the system to green roofs.

Task 3 – 60% Complete

Quantify the potential environmental, economic and social benefits at the watershed scale.

Stormwater runoff from standard urban development practices causes negative externalities including effects on health, recreation opportunities, and environmental amenities (Young, 2000). GRs increase social well-being and environmental quality by decreasing stormwater runoff volume, flooding, combined sewer overflows, and wastewater treatment volumes (Niu et al. 2010; Clark et al. 2008; Thurston et al. 2003). There is evidence that GRs also decrease building energy consumption, increase roof longevity, mitigate the urban heat island effect, and capture air pollutants (Niu et al. 2010; Philadelphia 2009; Diblasi et al. 2009). Using results from Task 2, we are using benefit transfer to perform an economic valuation of the GR intervention at the watershed scale using a nonlinear scaling method to reflect more realistic conditions. We are testing the hypothesis that the net present value of a given new GR depends on how much and where LIDs have already been implemented in the context of the watershed. The public benefits that are quantified are the savings from reduced sanitary and stormwater treatment volumes, savings from reduced grey infrastructure to manage combined sewer overflows, and willingness to pay for decreased street flooding. The private benefits considered are energy savings. The capital cost and operation and maintenance cost between conventional and green roofs are also considered.

<u>Task 4- 60% Complete</u>

<u>Generalize the approach so that other or a combination of LID/BMPs can be tested and evaluated for their effectiveness.</u>

The site hydraulic model (Hydrus-1D) and the watershed model (IUHM) are generic models, although they need to be calibrated to a particular application site. The scaling-up modeling procedures to identify the system level economic and environmental benefits and the economic assessment procedures are also being developed as general tools for any LID/BMP in any areas. Given these conditions, we will generalize the approach so that other or a combination of LID/BMPs can be tested and evaluated for their effectiveness in any area.

Principal Findings and Significance:

<u>Task 1</u>

The instantaneous measured rainfall and runoff on the green roof and the calibrated and validated runoff hydrographs are shown in Figures 1 and 2. Summary statistics of the measured, calibrated, and validated runoff data are provided in Table 1. The modeled time to peak runoff rate for all storms is within 5% of the measured values. The measured and simulated peak runoff rates are generally within 20% except for storm 1 with a relative percent error of 63%. The relative errors between the calibrated and measured total volume of runoff are 36 and 44% for storms 1 and 2, respectively, and less than 1% error for storms 3 and 4.

Table 1: Statistics for the measured and modeled runoff for the calibration and validation

	Storm 1	Storm 2	Storm 3	Storm 4	Storm 5	Storm 6	Storm 7	Storm 8
Peak Measured *RO (cm)	0.028	0.005	0.006	0.001	0.005	0.008	0.010	0.006
Peak Simulated RO (cm)	0.046	0.006	0.006	0.001	0.009	0.006	0.009	0.011
****RPD between measured and simulated peak RO rate**	65.14	22.51	-2.82	15.20	79.60	-23.06	-10.41	94.30
Time to Peak Measured RO Rate (mins)	109	1186	347	315	458	211	48	43
Time to Peak Simulated RO Rate (mins)	113	1202	361	303	463	235	73	54
RPD between measured and simulated time to peak RO	3.67	1.35	4.03	-3.81	1.09	11.37	52.08	25.58
Total Measured RO (cm)	2.03	2.50	2.00	0.12	1.31	0.77	0.58	0.41
Total Simulated RO (cm)	1.29	3.60	2.01	0.12	1.75	0.69	0.83	0.95
RPD between measured and simulated total RO	-36.76	44.18	0.63	0.22	33.65	-11.09	43.82	135.58

*RO: runoff, **RPD: relative percent difference

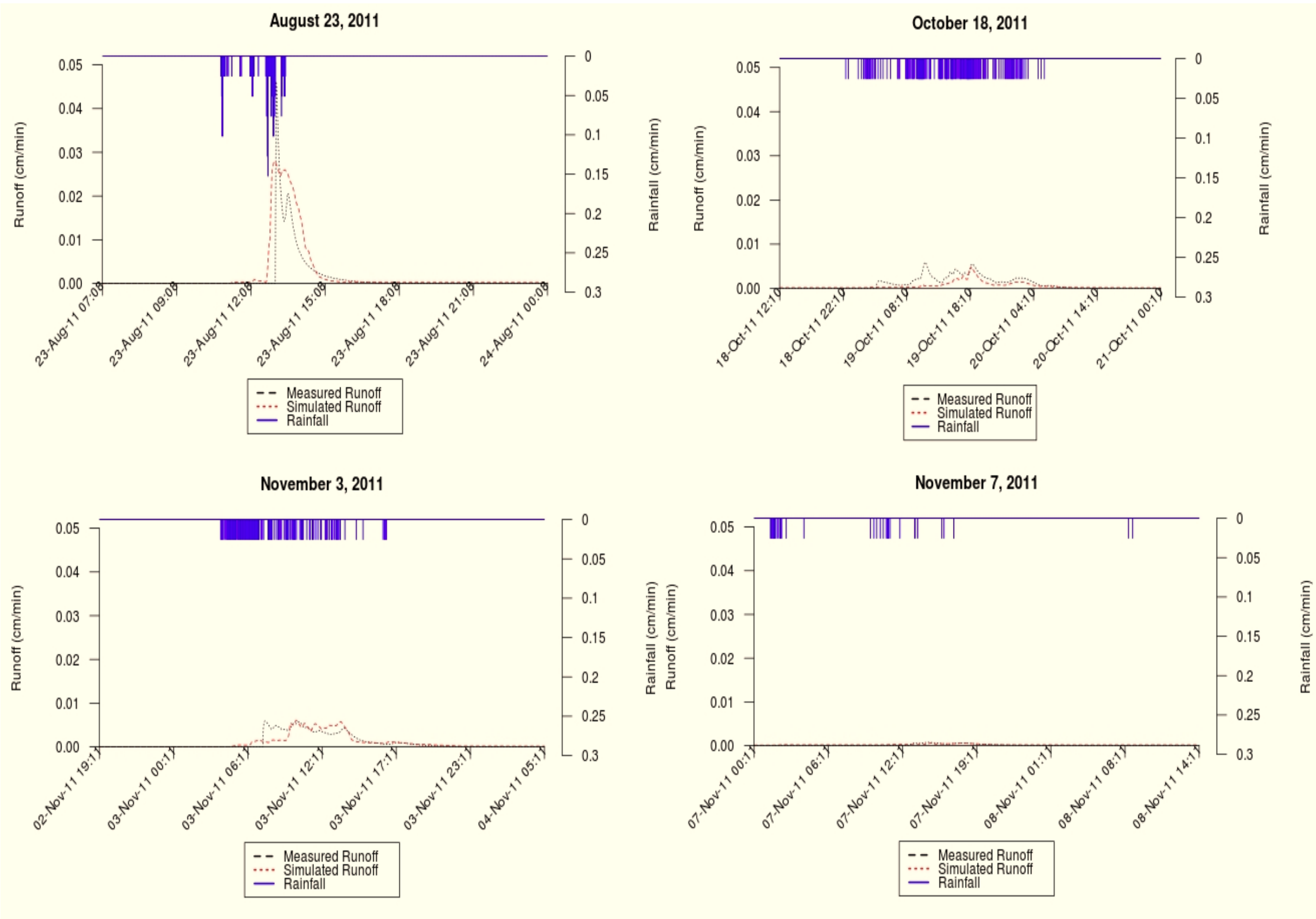

Figure 1: Measured and modeled runoff hydrographs leaving the green roof for calibration storms

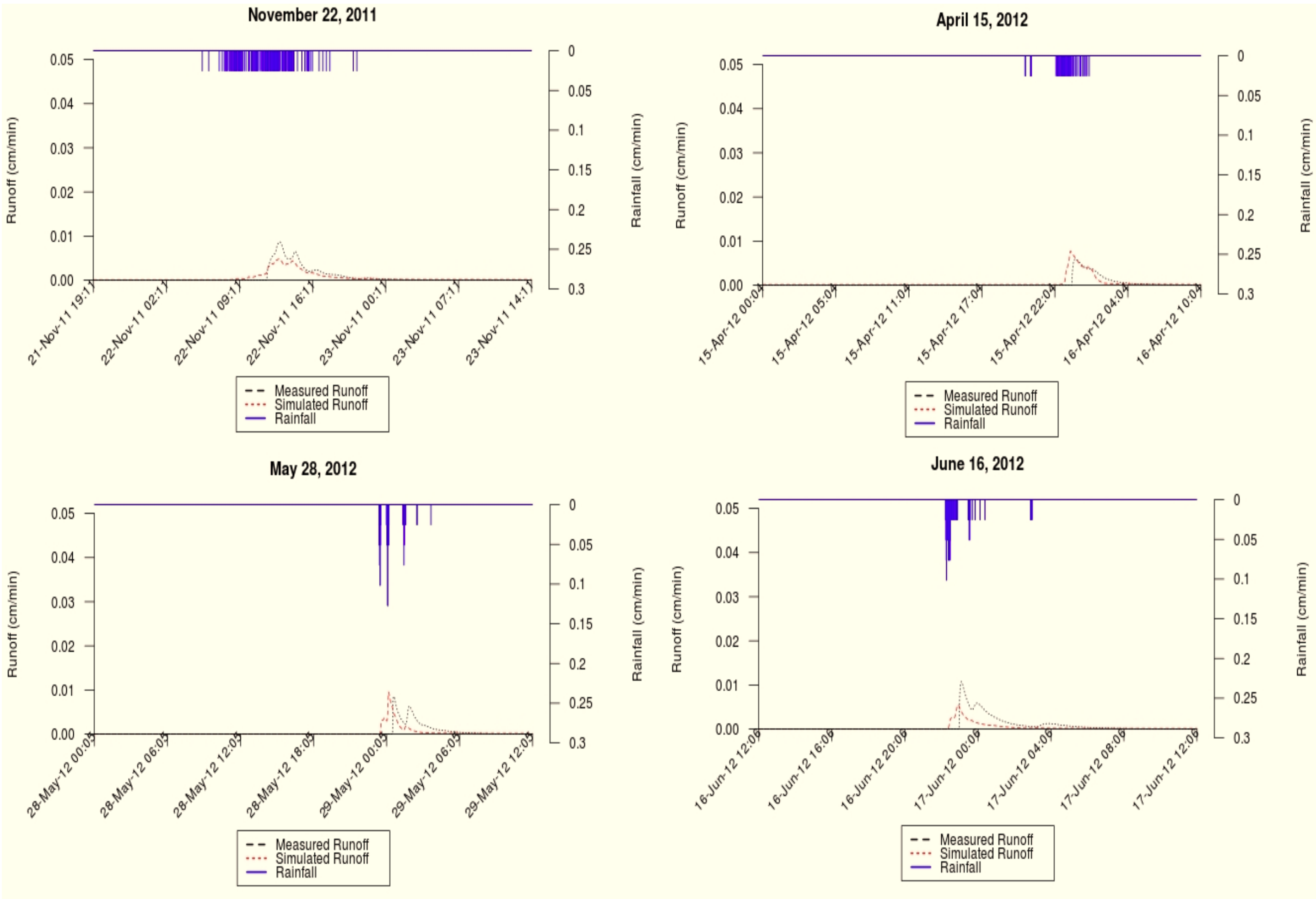

Figure 2: Measured and modeled runoff hydrographs leaving the green roof for validation storms

Simulated total runoff volumes for all validation storms are within 44% of observations, except for storm 8; i.e., the peak runoff rate is over predicted by 100%, total runoff volume is over predicted by 137%, and time to peak is within 25%. This is most likely due to measurement errors based on the observations that only 0.4 cm of runoff were generated for 1.5 cm of rainfall, and other storms of similar size and initial conditions had a greater fraction of the rainfall runoff. The peak runoff rate is over predicted by 50% for storm 5, while it is within 23% and 10% for storms 6 and 7, respectively. These errors are comparable to the relative percent errors calculated by Palla et al. (2009).

The double mass curves of measured and simulated runoff volumes with respect to total rainfall volumes for the calibrated storms are shown in Figure 3. Of the 13.1 cm of rain considered over the four month period, the green roof releases 8.4 cm of runoff and retains 4.7 cm, or 36.2% of the total rainfall. The high R^2 indicates that the observed and predicted runoff values are correlated. The predicted total runoff falls within 0.51 cm of the observed total runoff.

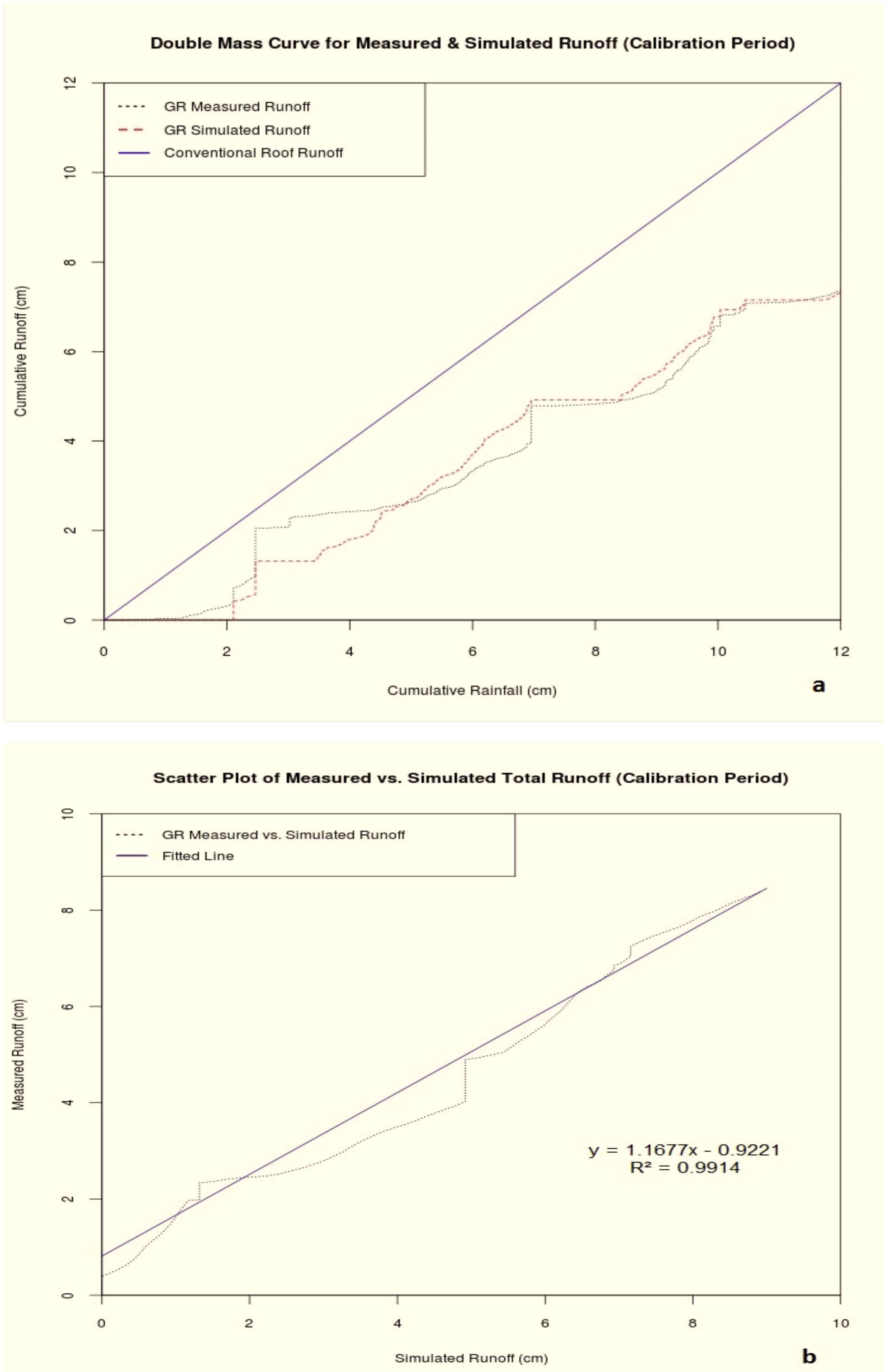

Figure 3: a) double mass curves for calibration storms, b) scatter plot of measured vs calibrated runoff

The double mass curves for the period between March – June 2012 are shown in Figure 4. For 11.6 cm of rain, the green roof retains 71% (or 8.1 cm) of the total volume. The double mass curves generated by the measured and modeled runoff differ by 1 cm for the four months period considered and are correlated as indicated by the high R^2 value. For both the calibration and validation storms, the predicted total runoff volumes are within 30%.

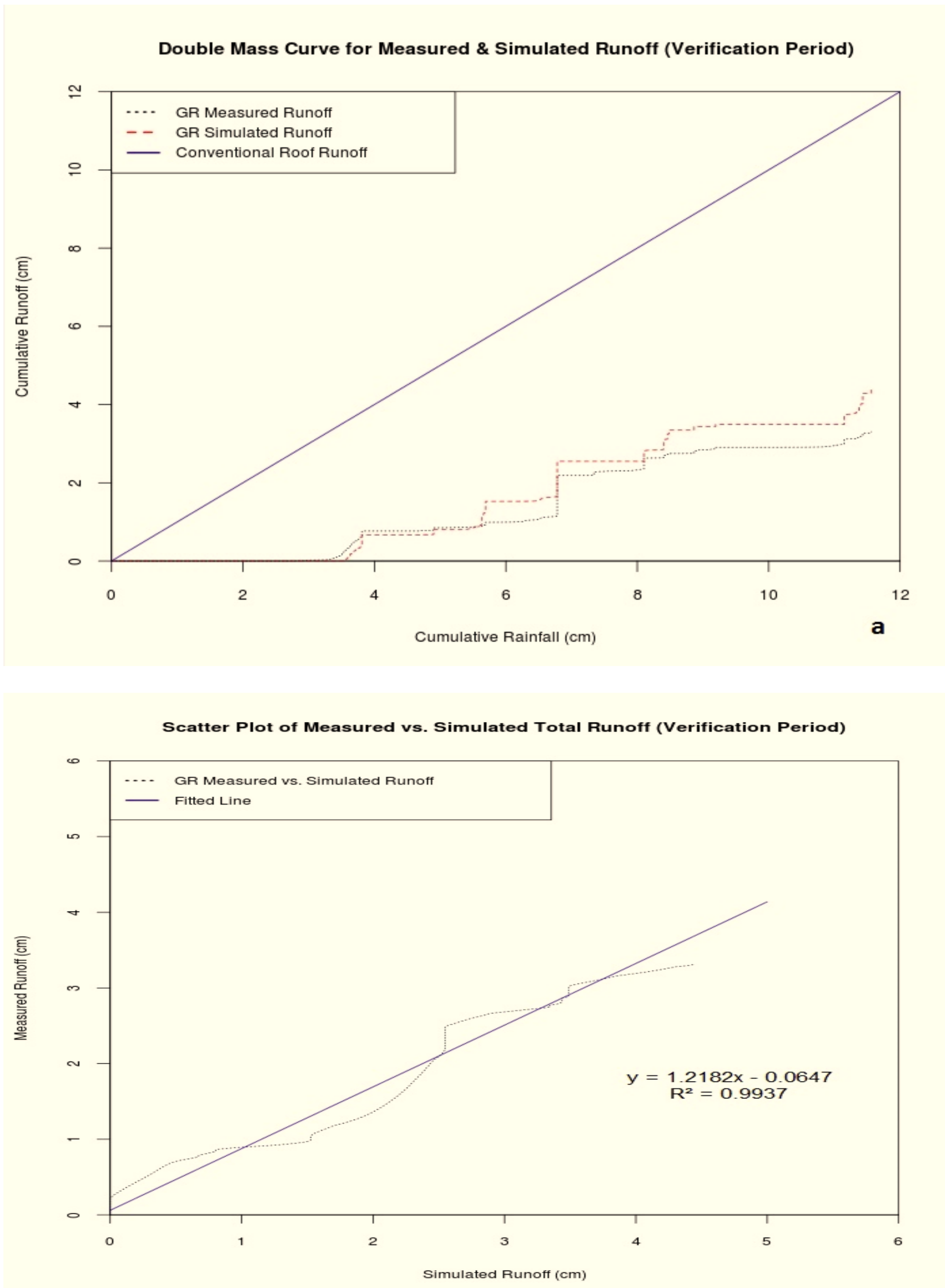

Figure 4: a) double mass curves for calibration storms, b) scatter plot of measured vs verified runoff

Task 2

Green roof coverage in the watershed is controlled by introducing a variable, *gr_ratio*, which is a percentage of the impervious area that would be replaced with green roofs. Figure 5 illustrates how the GR response to a storm that occurred on August 23, 2011, is incorporated into the watershed model (IUHM). It is assumed that green roofs are replacing directly connected impervious areas. The figure illustrates how a new equivalent rainfall event can be derived for the new, reduced impervious area by superimposing the original rainfall intensity with the synchronized green roof runoff response to the August 23, 2011 storm. This method conserves the volumetric rainfall falling on the watershed and accounts for the delayed runoff response due to the addition of green roofs.

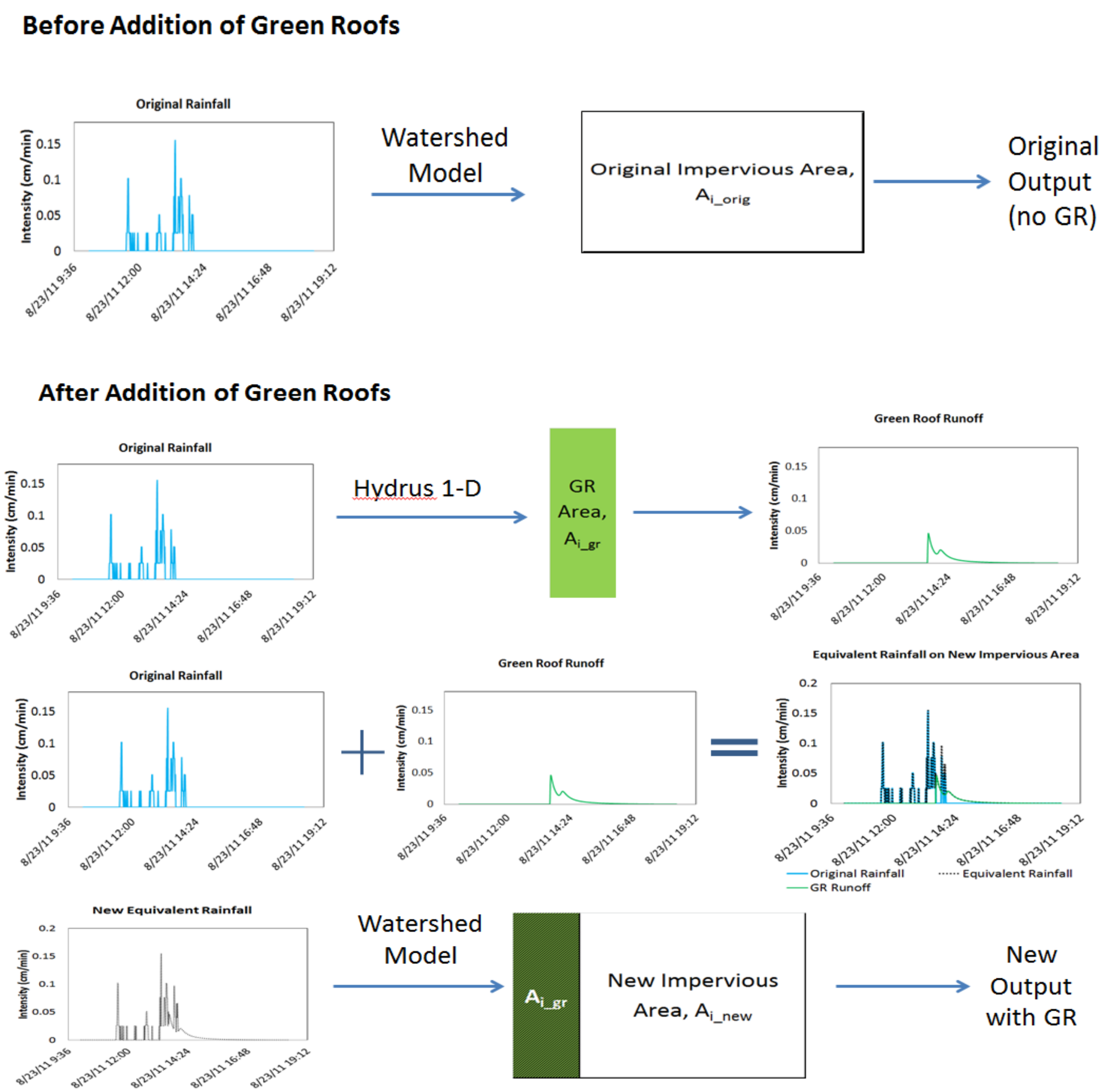

Figure 5: Incorporation of GR response into IUHM

Figures 6a and 6b show the watershed response for a hypothetical uniform and 5-year ARI (Average Return Interval) triangular storm generated by the methodology proposed by Yen and Chow (1980) for different percentages of green roof coverage. Hypothetical uniform and triangular storms are chosen in order to capture the response characteristics of green roofs to simple rainfall series and to rule out any doubts that the watershed response may be a function of rainfall. The uniform storm is a low-intensity/short-duration event and the 5yr ARI storm is a high-intensity/short-duration storm.

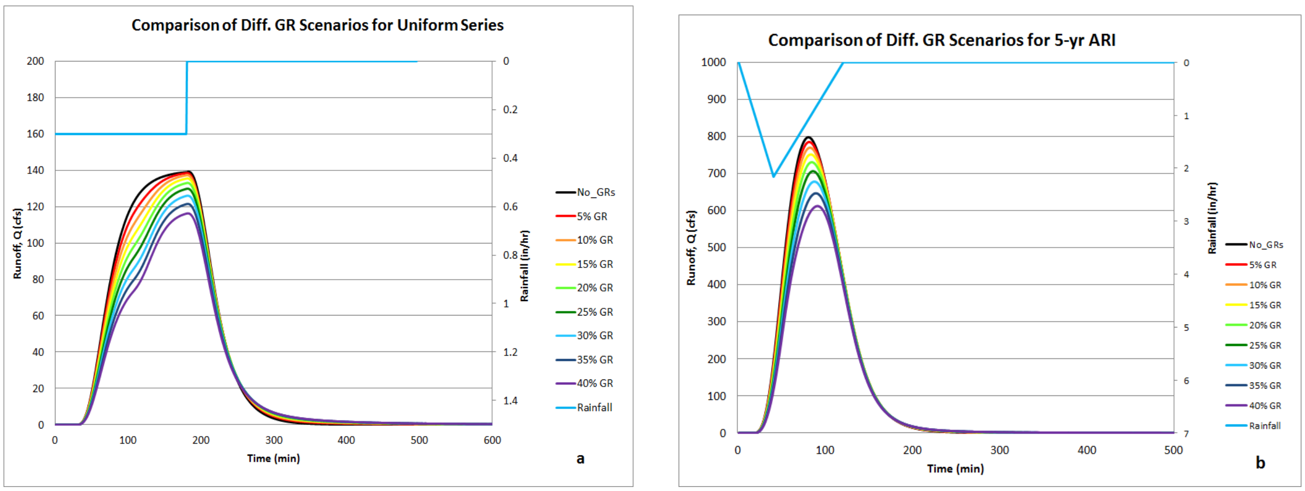

Figure 6: Watershed response to a) uniform and b) triangular storms under different GR coverage scenarios

Two real rainfall events from Dolton, IL were also used: a long-duration, low intensity, January 2008 storm and a short-duration, high intensity November 2011 storm. Results are shown in Figures 7a and 7b.

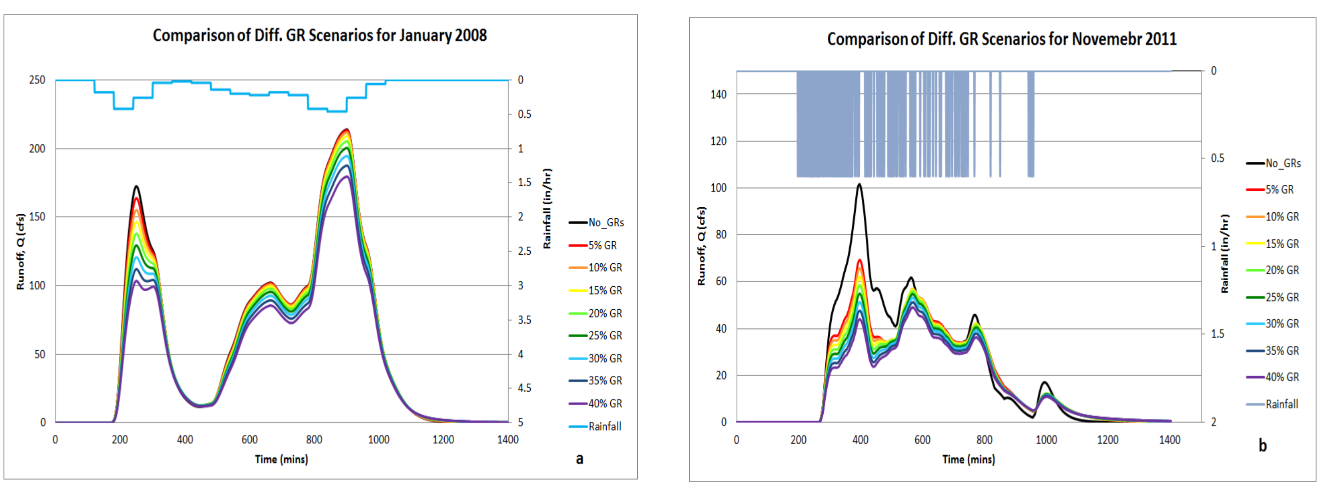

Figure 7: Watershed response to the a) January 2008 and b) November 2011 storms under different GR coverage scenarios

Task 3

Storage Cost

Municipalities can deal with CSOs by upgrading and enlarging existing grey infrastructure or using offline storage such as surface storage tanks, deep tunnels, detention basins, and retention basins. For urbanized areas, real estate for offline storage of stormwater is often unavailable and very expensive to invest in. This is where green roofs may be advantageous since they do not require any additional real estate. Heaney et al. (2002) provide an empirical cost for surface storage (equation 1) and deep tunnels (equation 2) which relates the cost as a function of size or volume:

$$C = 4.546V^{0.826} \qquad \text{(eq 1)}$$

where
C = construction cost for surface storage, millions $
V = volume of surface storage, Mgal ($0.15 \leq V \leq 30$ Mgal)

$$C = 6.228V^{0.795} \qquad \text{(eq 2)}$$

where
C = construction cost for deep tunnel storage, millions $
V = volume of deep tunnel storage, Mgal ($0.15 \leq V \leq 30$ Mgal)

Reduced Treatment Cost

Johnston and Braden (2004) stress that treatment savings are site-specific and that the benefits cannot be generalized across sites. Wise et al. (2010) suggested a simplified approach to treatment cost per gallon by using the treatment expenses that a local utility incurs. They used the Center for Neighborhood Technology's (CNT) Green Values Calculator which estimates MWRDGC treatment cost as $29.94 per acre foot.

Lifecycle Costs

The Green Values National Calculator developed CNT uses a 3.1% discount rate for life cycle assessments. Clark et al. (2008) and Niu et al (2010) performed net present value analysis to compare the benefits of green roofs over conventional roofs in reducing stormwater, energy, and air pollution. They included the installation costs for conventional and green roofs but did not take into account annual operation and maintenance cost since they assumed that they are incurred only during the first two years, until plants are established, and represent a very small fraction of the total cost.

The National Green Values Calculator is a tool developed by CNT that has compiled performance, costs, and benefits of low impact development and conventional stormwater practices. Midrange cost estimate values were used for the construction cost of each roof type: $7.50/sq ft for traditional roofs and $15.75/sq ft for green roofs. It was assumed that traditional roofs require no maintenance (unless there is damage) and green roofs require maintenance for the first two years until the plants are established. The plants and soil matrix of green roofs offer added insulation to a building and added cooling through evapotranspiration. Banting et al. (2005) reported direct energy savings of 4.15 kWh/sq. m/year for a green roof compared to conventional roofs. The cost of electricity in the Chicago area is $0.153/kWh (BLS, 2012).

Nonmarket Valuation

The economic approach to valuation is an anthropocentric approach based on utilitarian principles. An anthropocentric approach assumes that human beings assign value on goods/services or other species based on their usefulness to humans. Utilitarian values stem from the ability to provide welfare or overall well-being to an individual or group of individuals based on human preferences. It also assumes that there is potential for substitutability between the different sources of value that contribute to human welfare. Societal values are the aggregation of individual values assigned by the individual's preferences or marginal willingness to trade one good or service for another (NRC, 2004). Methods for determining nonmarket values include revealed preference, stated preference, and avoided cost analysis.

For our study we used results from a choice experiment (CE), a stated preference method. CE analysis assumes that utility is derived from the different attributes of a good rather than the good itself and tries to estimate a value for each utility (Londono and Ando 2011). Londono and Ando (2011) applied a CE valuation method to estimate people's willingness to pay (WTP) for several outcomes of green stormwater management in Champaign-Urbana, Illinois. Respondents were provided with background information about stormwater management problems and ways to control them, and then presented with six management choices with varied values. The six attributes were frequencies of street, backyard, and basement flooding, surface water quality, groundwater infiltration, and cost (stormwater utility bill). Respondents could choose from current stormwater management levels, three proposed levels of stormwater management, and no new stormwater management projects. The respondents were then asked for their willingness to pay for distributed stormwater controls on their property. The results of the survey indicate that people place positive value on hydrological improvements associated with LID and are willing to pay \$0.4984 per percent decrease in flooding frequency and \$ 0.5637 per percent increase in infiltration rate.

Figure 8 shows plots of the marginal costs and benefits incurred with green roof intervention at the watershed scale. The savings are calculated with respect to the base scenario of no green roofs and they include savings in energy usage, water treatment, increased infiltration, avoided infrastructure cost, and decreased street flooding. The costs incurred are due to installation of green roofs and their operation and maintenance cost. A 36-year lifecycle analysis is used since this is the typical lifetime of a green roof. During this period, a typical conventional roof with a life cycle of 16 years would have to be replaced twice. The values are conservative since it is assumed that each of the events occurs once during the time period of analysis and hence the savings in treatment costs occur once. In reality, the treatment cost savings will be greater and future research will take into account the frequency of occurrence of each event. Green roofs do not increase groundwater infiltration but they do increase evapotranspiration. The WTP for infiltration can be used as a proxy for increased restoration of the natural hydrologic cycle through increased evapotranspiration. All plots of total marginal benefits show an increasing slope with increased green roof coverage. These results indicate that benefits either keep increasing as impervious cover is replaced with pervious surfaces in a watershed or that due to the constraint of 40% green roof coverage, the threshold of benefits could not be observed for this watershed.

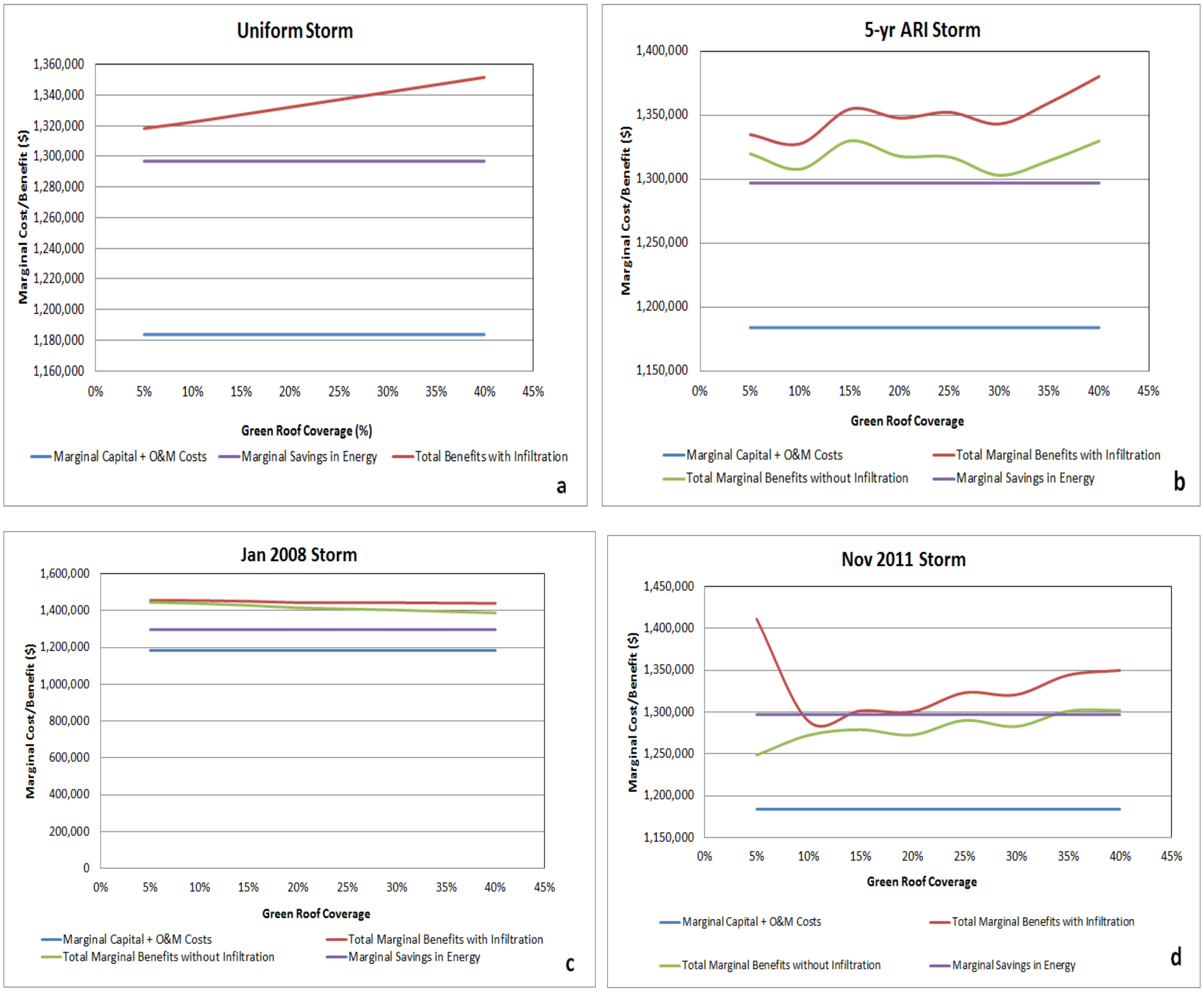

Figure 8: Total marginal benefit/cost curves for a) uniform storm, 5-yr ARI storm, c) January 2008 storm, d) November 2011 storm

Notable Achievements

- Calibrated and validated a mechanistic model to simulate green roof water flow taking into account inter-event processes
- Developed a method to integrate site-scale green roof performance into a watershed model in order to quantify the hydrological and economic impacts of green roofs in an urban area.

Student Supported

Najwa Obeid, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, PhD, Expected December 2014

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