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Proposing A Framework for Crowd-Sourced Green Infrastructure Design

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Abstract: Green stormwater infrastructure (GI) (e.g., rain gardens, bioswales, green roofs, etc.) are decentralized systems that have gained recent attention for their ability to reduce stormwater management problems while significantly benefiting human and ecosystem well-being. Available GI design methodologies lack a participatory framework that considers community-specific social, cultural, economic, and political constraints, critical components for widespread acceptance and effective implementation and maintenance of such systems. A project funded by the U.S. National Science Foundation seeks to develop a novel, computational, GI design framework that integrates interactive, neighborhood-scale, collaborative design by multiple stakeholders ("crowd-sourced" design) with multi-scale models of ecosystem and human impacts. The primary research tasks include: (1) creation of integrated models to predict hydrologic, human, and ecosystem impacts of GI designs from site to catchment scales, (2) development of interactive methods for crowd-sourcing model parameterization and GI design, and (3) implementation of modeling and crowd-sourced design methods in a cyberinfrastructure (CI) framework. The models developed in this project will be among the first to integrate criteria for human wellbeing with site-and-watershed-scale hydrologic and ecologic processes. Furthermore, by advancing crowd-sourced interactive optimization and model parameterization, this project can influence other design processes where early, diverse input is important for design acceptance.

Keywords: green infrastructure; stormwater management; cyberinfrastructure; crowd-source design; socio-ecohydrology

1 INTRODUCTION

Urbanization has contributed to increasing stormwater runoff and pollutant loads, reducing ecosystem nutrient retention, and creating poor water quality and ecosystem health downstream (NRC, 2008; Wendel et al., 2011). Loss of tree canopy and expansion of impervious area and storm sewer systems have significantly decreased infiltration and evapotranspiration, increased streamflow velocities, and increased flood risk. These problems have brought increasing attention to catchment-wide implementation of green infrastructure (GI) (e.g., decentralized green stormwater management practices such as bioswales, rain gardens, permeable pavements, tree box filters, cisterns, urban wetlands, etc.) to replace or supplement conventional stormwater management practices and create more sustainable urban water systems (Dietz, 2007; Roy et al., 2008; Sullivan et al., 2010). Current GI practice has the goal of mitigating the negative effects of urbanization by maintaining or restoring pre-development hydrology (Dietz, 2007) and ultimately restoring aquatic ecosystems and addressing water quality issues at the catchment scale (Burns et al., 2012; Filoso and Palmer, 2011; Walsh et al., 2005).

Despite increased attention to GI, current urban GI design methodologies do not adequately integrate site-scale design decisions with catchment-scale impacts. Municipal stormwater managers and homeowners, for example, make decisions at the site scale (i.e., the scale of a patch, a land areas with relatively uniform physical and biological characteristics, or parcel, a legal or management area that may have multiple patches), and may receive credits for expected pollutant reductions. It remains difficult to estimate or verify the collective impacts of GI installations at catchment scales. Similarly, the benefits of GI extend beyond the scale of local stormwater control, since urban green spaces (e.g., lakes, parks, and community gardens) are major contributors both to the quality of the urban ecosystem and to human health (Morris, 2003; NRC, 2008; Wendel et al., 2011). Quality green spaces encourage people to walk, run, cycle, play, and engage in recreation that provides healthy physical activity and reduces mental stress (Maas et al., 2006; Morris, 2003). Green spaces also improve air quality and reduce noise pollution (Dunn, 2010; Pataki et al., 2011; Pincetl, 2007).

1.1 Contributions

We are developing a computational GI design framework that integrates stormwater management requirements with criteria for ecosystem health and human wellbeing. Stakeholders (e.g., homeowners, NGOs, city/regional agency, etc.) can interactively create and evaluate potential GI designs in a novel “crowd-sourced” design framework (Figure 1) that considers the full breadth of social, economic, and environmental criteria across scales. Computational elements of the framework combine innovative multi-scale modeling, interactive and collaborative visualization and optimization, and cyberinfrastructure (CI) to promote active community input to the planning and design of catchment restoration and management efforts. The models and algorithms are implemented in a scientific workflow system that utilizes computing resources in the Cloud and links to a Web interface enabling stakeholders to view, create, and rate GI designs. In addition to the cross-scale benefits, our framework can enable clear and timely communication between stakeholders by serving as a *boundary object* – a concept introduced by Star and Griesemer (1989) for objects (such as maps) that enable communication across disciplinary or social divides because they retain commonality even as different viewers see different things within them.

The models developed in this project will be among the first to integrate criteria for human and ecosystem wellbeing with site- and watershed-scale hydrologic processes, which are key for improved understanding and implementation of GI design. Moreover, by advancing crowd-sourced interactive optimization and model parameterization, this project can influence other design processes where early, diverse input is important for design acceptance. Map and image visualization will identify which visualization approaches best support achieving consensus in collaborative design.

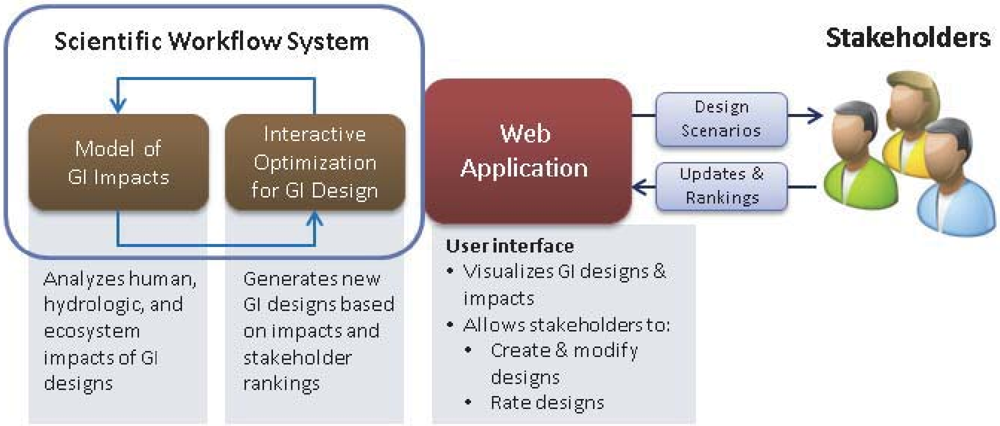

Figure 1. Computational crowd-sourced GI design framework

2 METHODOLOGY

Developing an effective crowd-sourced GI design system requires advances in modeling, information visualization, interactive optimization, and cyberinfrastructure. Thus, the main tasks associated with the development of the framework include: (1) creating integrated models to predict hydrologic, human, and ecosystem impacts of green infra-structure designs from site to catchment scales, (2) developing interactive methods for optimizing crowd-sourcing GI design, and (3) implementing the modeling and crowd-sourced design methods in a cyberinfrastructure (CI) framework. We describe each of these below.

2.1 Green Infrastructure Modeling

Current GI design guidelines provide site-specific (patch or parcel) design criteria but only qualitative discussion of catchment-scale impacts of multiple GI installations (e.g., CalTrans, 2010; City of Portland, 2008; Harper and Baker, 2007; MDE, 2009; NCDWQ, 2007). Practitioners typically use either site-scale design tools or catchment-scale lumped-parameter stormwater models (e.g., MARC 2008; Vassilios et al., 1997; and tools such as HSPF, SWMM and HEC–HMS) that do not represent detailed site-specific hydrology or GI processes. These models do little to incorporate ecosystem processes representing the continuous cycling and storage of water, carbon, and nutrients with time-varying hydroclimate conditions over a range of local ecosystem and landscape conditions; instead they use fixed retention rates for each GI practice, or first order retention parameters that adjust for flows and temperatures. Additionally, most of these models address surface water loading only and consider infiltration to be a sink, or loss from the system, without adequate coupling with groundwater. Furthermore, the arrangement and drainage sequence of flowpath features (e.g., from roofs to lawns, streets, and GI) has been modeled (e.g., Pitt and Vorhees, 2002, 2011) without adequate incorporation of the dynamics or kinematics of flows, biogeochemical processes, or subsurface flow response.

Rigorously considering ecosystem services in GI design, including carbon sequestration and nutrient retention, requires an integrated ecosystem process with a continuous, distributed hydrologic representation. Research from the Baltimore Ecosystem Study (BES) suggests that significant carbon sequestration and nitrogen retention can occur in a range of urban ecosystem features, including lawns, gardens, and stormwater detention structures, but that these processes are sensitive to specific characteristics of the integrated drainage system, including contributing areas, flow regimes, soils, and structure design (e.g., Bettez and Groffman, 2012; Raciti et al., 2011a,b). Design of sustainable GI should incorporate transient development as the ecosystem develops in response to local climate, soil, and drainage position (e.g., location within a flow field), including runoff source areas in addition to edge-of-field or in-line treatment systems.

We will address these challenges by coupling the Illinois Urban Hydrologic Model (IUHM) (Cantone and Schmidt, 2011), which builds a catchment-scale hydraulic routing network and performs probabilistic analysis of multiple flow paths, with RHESSys (Tague and Band, 2004), which builds a fine-scale continuous model of ecosystem patch dynamics (e.g., transport and cycling of water, carbon and nitrogen) (Figure 2). A mechanistic computation of coupled transport and cycling of water, carbon and nitrogen will be carried out within each patch using RHESSys and linked by the design flow topology to proximal stream and sewer drainage with IUHM during each time step. This has the advantage of explicitly representing short- to long-term ecosystem dynamics (e.g., carbon assimilation, organic matter decomposition, mineralization, etc.) within small source areas and the net retention effects of specific landscape and drainage sequence designs. In order to scale from neighborhoods and small catchments to larger urban and urbanizing catchments, we will modify the approach of Cantone and Schmidt (2011) to produce an urban ecohydrological model based on a probabilistic drainage sequence “holding time” and retention rate cascade for water, carbon and nitrogen. The underlying representation links the ecosystem dynamics of source area patches along a drainage sequence with catchment-scale routing to better simulate the site- and catchment-scale physical, chemical, and biological response of specific GI and land management practices.

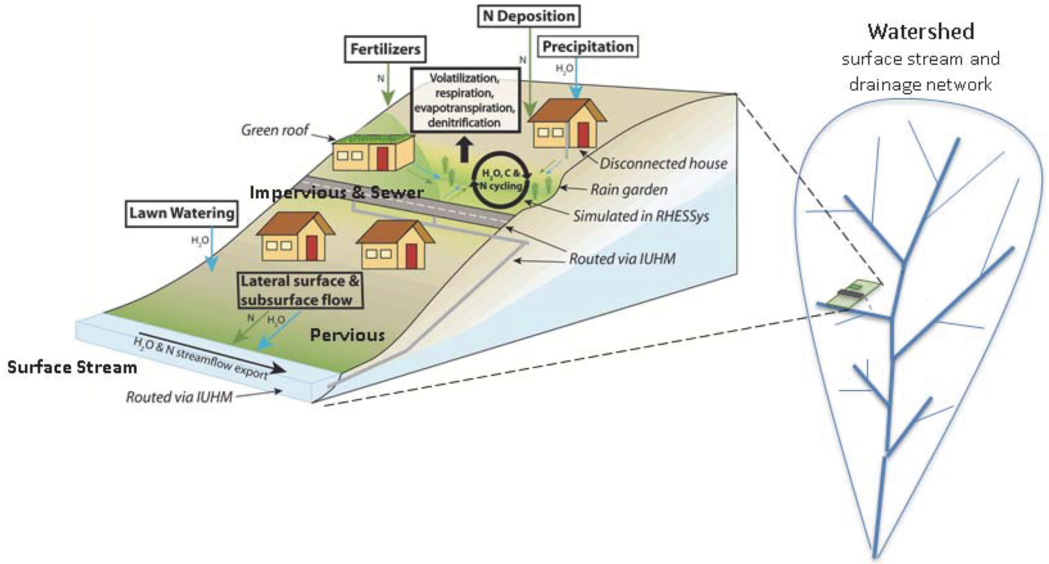

Figure 2. Ecosystem patch modeling using RHESSys, linked to sewer & stream drainage networks using IUHM catchment routing network.

2.2 Human Impacts of Green Infrastructure

Urban green spaces have profoundly positive impacts on individuals and communities. Forty years of research has established the powerful and consistent effects of the presence of natural elements in increasing preference for urban landscapes (for review, see Kaplan and Kaplan, 1989). These elements, in turn, are now associated with a variety of health benefits including faster recover from stressful experiences, reduced physiological symptoms of stress (Chang and Chen, 2005; Thompson et al., 2012), and increased life expectancy (Mitchell and Popham, 2008; Takano et al., 2002).

Both the content of green settings and the arrangement of that content predict wellbeing (Kaplan and Kaplan, 1989). Green settings that are well organized (coherent) and display distinctive features (legible) attract people and engage them longer than less coherent or legible green settings. Green settings that have some complexity and mystery (e.g., when a path is partially concealed by foliage) are highly preferred by urban residents (Sullivan et al., 2004). These types of stakeholder preferences cannot be easily reduced to engineering requirements, thus visual depictions are critical to evaluating potential GI designs.

To address these complexities, we are developing a novel machine learning model that maps landscape features, which are correlated with human wellbeing, to features that can be extracted from design images. A preliminary feature extraction model has been developed using image processing techniques combined with K-Nearest Neighbor with adaptive boosting, but other methods such as spatial pyramid matching (Lazebnik et al., 2006) are also being explored. The features that lead to high or low preference ratings are extracted using image segmentation algorithms (Anami et al., 2010) and then used to train a machine learning model that predicts human preference. To identify which image features to include in the model, image segmentation algorithms are coupled to Kaplan and Kaplan (1989)'s human preference matrix for urban green spaces, which gives GI characteristics that are most linked to human wellbeing. This framework creates the first GI design tool to predict human health benefits of GI from green-space images based on previous research in the environmental psychology field.

2.3 Interactive Optimization

Interactive and collaborative design, in which multiple stakeholders are engaged in evaluating candidate design proposals, addresses recent concerns that environmental design for efficiency alone can lead to unsustainable solutions and stakeholder resistance (Brock and Carpenter, 2007; Ostrom et al., 2007). Previous interactive optimization applications (e.g., Babbar and Minsker, 2008; Ibarbia et al., 2012; Klau et al., 2010; Lin et al., 2010; Singh et al., 2008) have typically involved a single stakeholder or decision maker evaluating potential solutions subjectively (e.g., ranking solution preference 1–5). Including expressed preferences in the optimization can reduce the time to convergence and reach solutions that better represent the subjective preferences of decision makers (Babbar and Minsker, 2008; Klau et al., 2010; Munda, 1993; Roy, 1990). Interaction also allows incorporation of human skills in areas where humans outperform computers, such as visual perception, strategic thinking, and the ability to learn (Klau et al., 2010). These characteristics make interactive optimization a suitable choice for GI design, where many of the benefits to ecosystem and human wellbeing can be difficult to quantify mathematically.

We are developing new crowd-sourced optimization methods to synthesize input from multiple stakeholders and designers and build consensus. As stakeholder evaluations of candidate designs are received, ranking aggregation techniques (Fields et al., 2013; Wang et al., 2005) will be used to combine crowd-sourced rankings of GI designs from multiple stakeholders into a single overall ranking of each design. A multi-objective genetic algorithm (GA) will then be used to generate new designs for further evaluation and evolve candidate designs toward those with high human and ecological benefits. Users will also be able to propose or modify designs that would be added to the population for evaluation and further modification by other users or the GA. Lastly, the human preference model described in section 2.2 will be used to generate a small set of diverse and promising initial designs for stakeholder evaluation, which will reduce user fatigue (Singh et al. 2008), improve understanding and prediction of stakeholder preferences over time, and facilitate stakeholder engagement.

2.4 Visualization

Visualization is essential for communication within the design loop (Ware, 2008). Visualization scenarios are classified based on several characteristics: size of audience (individual, small group, public forum), level of interactivity (moments to months to incorporate changes and give feedback), and symbolic vs. representational (map vs. image). Ware (2012) points out that problem solving with diagrams or maps is very different than without, and that part of the thesis of active perception is that our brains do not try to make a model of the entire world, but are content to use the world, and therefore diagrams or maps, as external storage that can be accessed by our visual processing.

The task of creating useful visualization and design tools is complicated by the diversity of disciplines and stakeholders, by the sizes of data sets and models, and by the wide array of interaction technologies. Success requires an interdisciplinary team that can formulate a common vocabulary of data, design options, and design goals, and make this accessible to a larger group of stakeholders. This is best done through rapid development of prototypes that are anchored in specific scenarios of stakeholder interaction to mediate between conflicting goals, such as accurate modeling and interactive response times (Brooks, 2010).

We use standard infrastructure to create visualizations for multiple pre-specified scenarios; the novelty of the approach lies in what map- and image-based visualizations (e.g., 3D rendering of different types of GI imbedded in Google Street View) best support collaborative design. To support interactive crowd sourcing of model parameters (e.g., allowing users to identify downspout and storm drain locations, provide information about household owned GI and actual water flowpaths [e.g., impervious -> pervious], correct modeled household flooding level, etc.) and optimization of GI designs, commercial and entertainment efforts will be leveraged to present the world and to merge real and virtual images. The methods and tools will be tested by our team and collaborating partners to identify the most promising for rigorous testing.

2.5 Cyberinfrastructure

A project that involves combining two hydrologic models and two machine learning algorithms, interacting with a variety of stakeholders to incorporate their preferences and values, requires software tools that support capturing scientific workflows and merging data ontologies in a way that is accessible and reproducible, requires an advanced cyberinfrastructure. The GI design framework will be implemented in CyberIntegrator, an open source workflow system developed at the National Center for Supercomputing Applications (NCSA) (Kooper et al., 2007). Scientific workflows chain computational steps that access, analyze, model, and visualize data in a provenance-preserving manner, allowing users to automatically capture and archive various execution configurations with associated data inputs/outputs (Deelman et al., 2005; Kooper et al., 2007; Moreau et al., 2012). CyberIntegrator is the workflow system selected for this project because of its ease of integrating heterogeneous software developed by multiple teams, its capabilities for accessing remote services in heterogeneous computing environments, and its exploratory interface to build workflows without programming (McHenry et al., 2011; Kooper et al., 2007).

In addition, data within and from the models must have a shared meaning or ontology. To address this requirement, the capabilities of the integrated Rule-Oriented Data System (iRODS) will be coupled with the workflow system. iRODS is a community-driven, open source, data grid software solution that provides flexible distributed data curation via customizable collections of rules for actions during data ingestion and replication (Rajasekar, 2010). iRODS' power lies in the policy engine that overlays the file store. When multiple independent systems can rely on a centralized, stateful engine, they can work together without having to interact directly with one another.

3 CASE STUDY

The performance of the developed GI design framework will be evaluated in three urban catchments in the Baltimore Ecosystem Study, where community GI is being rigorously studied and implemented, and extensive existing data on pretreatment stormwater and nutrient conditions are available. The catchments are in distinctly different residential areas that have been monitored for more than a decade, including continuous stream outflow, weekly stream chemistry, and periodic “synoptic” sampling (sampling multiple locations along the stream network). These data will be used to calibrate and validate the hydrologic and ecosystem models. Environmental non-governmental organizations (NGOs) in Baltimore will provide access and interface with communities that are currently implementing GI. Their input will be used to evaluate and improve predictions of human GI preferences, the efficacy of the crowd-sourced design framework, and improvements in stakeholder engagement in GI design through interactive CI.

4 CONCLUSION

We are developing a novel computational GI design framework that integrates interactive, neighborhood-scale, collaborative design by multiple stakeholders (“crowd-sourced” design) with multi-scale models of ecosystem and human impacts. The novelty of the project lies in the development of models that will integrate for the first time criteria for human wellbeing with site- and watershed-scale hydrologic and ecologic processes, as well as advancing interactive optimization approaches and model parameterization into crowd sourcing methods. Furthermore, map and image visualization will identify which visualization approaches are most supportive in achieving consensus in collaborative design, thus providing the first evaluation of interactive CI for improving stakeholder engagement. Finally, the developed framework will be evaluated using the BES as a case study, working closely with community partners, ongoing studies, and GI implementation efforts in Baltimore. These interactions will not only improve the models and framework but will ensure that the results will provide significant benefits to community stakeholders.

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