



Research

Adapting the social-ecological system framework for urban stormwater management: the case of green infrastructure adoption

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ABSTRACT. Stormwater management has long been a critical societal and environmental challenge for communities. An increasing number of municipalities are turning to novel approaches such as green infrastructure to develop more sustainable stormwater management systems. However, there is a need to better understand the technological decision-making processes that lead to specific outcomes within urban stormwater governance systems. We used the social-ecological system (SES) framework to build a classification system for identifying significant variables that influence urban stormwater governance decisions related to green infrastructure adoption. To adapt the framework, we relied on findings from observations at national stormwater meetings in combination with a systematic literature review on influential factors related to green infrastructure adoption. We discuss our revisions to the framework that helped us understand the decision by municipal governments to adopt green infrastructure. Remaining research needs and challenges are discussed regarding the development of an urban stormwater SES framework as a classification tool for knowledge accumulation and synthesis.

Key Words: *green infrastructure; social-ecological systems framework; stormwater management; technology adoption*

INTRODUCTION

The lack of well-integrated urban stormwater management strategies throughout the past century has left a heritage of environmental and social problems that policy-makers continue to deal with today. Municipal stormwater management plans in many developed countries have favored the use of gray infrastructure (e.g., sewer separation projects, deep storage tunnels, and regional treatment facilities). These engineering solutions can be costly, tend to promote centralized subsurface conveyance systems with end-of-pipe treatment, and often take years to complete. Despite major investments in stormwater infrastructure, urban areas continue to experience critical problems in managing water flows, including flooding, surface water impairment, and combined sewer overflows (USEPA 2004, National Research Council 2009, Coles et al. 2012).

Recent advances in stormwater management methods seek to enhance the sustainability of urban water systems. For instance, stormwater systems that include green infrastructure (GI), also known as low impact development, are recognized as a more sustainable approach. GI technologies are designed to protect or restore the natural hydrology of a site, capturing stormwater volume through the use of engineered systems that mimic natural hydrologic systems. Comprehensive GI programs can be implemented for a variety of outcomes, including flood control, surface water quality improvement, and water harvesting, in conjunction with a broad range of additional outcomes such as ecosystem restoration, air quality improvement, and urban heat reduction (Hatt et al. 2004, Villarreal et al. 2004, Walsh et al. 2005, Tzoulas et al. 2007). However, there are potential practical limitations for GI to achieve sustainable outcomes for municipalities, such as a limited capacity for storing and infiltrating stormwater.

The decision to adopt a comprehensive GI program is influenced by a complex array of social and biophysical factors. To explore such complexities, an urban water system can be understood as a social-ecological system (SES), or a collection of dynamic

systems that coevolve through interactions among actors, institutions, and water systems, such as source water, groundwater, wastewater, and stormwater (Berkes et al. 1998, Holling and Gunderson 2002). The stormwater flows and storage volumes within an urban water SES represent common-pool resources, in that water quality and available storage volumes are diminished as runoff flows through urban environments. These issues prompt the need for public authorities to establish various standards related to the management of stormwater.

A fundamental component of urban stormwater SESs is the role of technology as a critical interface between the social and ecological structures, which allows actors to shape different processes to achieve outcomes in system functioning (Ferguson et al. 2013). Technologies also act as a feedback mechanism between the social and biophysical systems of an SES. Walker et al. (2004) describe the potential of an SES intervention to create a new system when the conditions of an existing system are weakened. Stormwater management systems that are exclusively composed of gray infrastructure may result in urban water system weakening because these technology systems are considered neither sustainable nor sufficiently resilient to accommodate climatic changes, and may result in unforeseen outcomes such as high economic costs and environmental justice issues (Pahl-Wostl 2007, Novotny et al. 2010, Dominguez et al. 2011, Pyke et al. 2011, Wendel et al. 2011, De Sousa et al. 2012). Alternatively, extensive use of GI in stormwater management represents an opportunity for transformational shifts in urban water SESs away from point source solutions to decentralized, systematic techniques that may also bring multiple benefits to communities (Shuster and Garmestani 2015).

There is a need to more easily relate attributes and configurations of urban stormwater SESs to particular outcomes, such as the development of comprehensive GI programs. Several frameworks exist which conceptualize and operationalize SES dynamics, each of which may provide different types of diagnostic insights. Thus, an analyst must be clear about the aim and purpose of any

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diagnostic procedure, and hence, which analytic framework will support the specific procedure being undertaken (Ferguson et al. 2013). Binder et al. (2013) provide an overview of the prevailing frameworks for analyzing SESs, and provide guidance on the selection of an appropriate framework. Scholars studying water systems have developed frameworks that identify key processes and structures affecting their governance (Pahl-Wostl et al. 2010, Wiek and Larson 2012). Because GI represents a suite of innovative technologies for many urban water SESs, it is necessary to first identify and define attributes that may prove to be significant in social-ecological interactions before establishing causal mechanisms linking conditions and governance outcomes. Providing a framework to organize and document SES attributes can serve this function.

Our primary goal is to identify the influential SES attributes related to the development of municipal urban stormwater programs that feature GI. We chose the SES framework because it provides a systematic and comprehensive method for defining system attributes and identifying those that are associated with outcomes of interest (Ostrom 2007, 2009). Numerous environmental case studies have applied the SES framework while adding or redefining attributes to best characterize the SES of interest (Fleischman et al. 2010, Gutiérrez et al. 2011, Cinner et al. 2012, Basurto et al. 2013, Nagendra and Ostrom 2014, Marshall 2015, Partelow and Boda 2015). No such effort has been previously undertaken to assess the suitability of the SES framework to characterize urban stormwater management systems. We use qualitative methods to identify and define the attributes most commonly associated with the inclusion of GI in municipal urban stormwater programs.

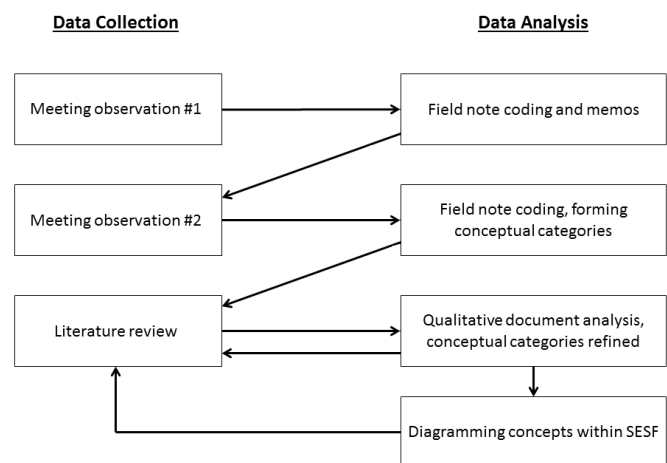
METHODS

The identification of attributes associated with GI adoption in municipal urban stormwater programs included several phases of data collection and analysis (Fig. 1). Exploratory work began with observations at GI summits in 2013 and 2014, in which delegates from U.S. municipalities were invited to discuss their respective community's GI programs. Extensive field notes from both meetings were coded line-by-line to identify factors that affected decisions to adopt municipal GI programs. The resulting codes were grouped into general categories of attributes that emerged during the analysis process. These categories were then incorporated into the SES framework, using first- and second-tier modifications, as suggested by McGinnis and Ostrom (2014), Epstein et al. (2013), and Vogt et al. (2015), as the initial framework.

Another stage of data collection included a literature review of original research efforts related to the adoption and implementation of GI in urban stormwater systems. Green infrastructure, green stormwater infrastructure (GSI), low impact design (LID), and best management practices (BMPs) are among the terms used for various suites of urban stormwater management technologies. We refer to GI, GSI, and LID technologies as "GI" because these terms are often used synonymously (Fletcher et al. 2014). Searches were carried out using Scopus, Web of Knowledge, and Google Scholar. Key words included in the literature review were "green infrastructure," "low impact development," "stormwater," and "municipal." Searches were conducted for studies published between 2000 and 2015. In total, 135 articles, theses, and reports were reviewed for their

relevance to factors affecting the adoption and implementation of GI technologies for municipal programs. Reasons for exclusion included a study focus on adoption of water systems other than stormwater (e.g., drinking water, wastewater), or an exclusive focus on GI technology design attributes outside the context of municipal stormwater management program implementation (e.g., experimental findings). Studies were not excluded on the basis of study design, the scale or primary design goal of stormwater technologies discussed, nor the geographical location of the study; however, most studies reviewed were based in the United States or Australia. This process resulted in 83 studies that met the criteria, and thus formed the basis of the review.

Fig. 1. Sequence of data collection and analysis. (SESF: social-ecological system framework)



Qualitative document analysis techniques were used to identify factors that influence municipal GI programs in each of the collected studies. These methods often involve the development of a "protocol," which is tested on each unit of analysis and revised based on the quality and likely efficiency of the results (Altheide et al. 2008). The SES framework adapted in the initial research phase served as a beginning protocol that consisted of identified attributes related to GI adoption. After analyzing each study of the literature review, new findings were organized within the protocol. After all studies were analyzed, each study was reviewed a second time to test the protocol. This process resulted in the addition or redefining of second-tier SES framework attributes and the development of new third-, fourth-, and fifth-tier attributes presented in Table 1. Working definitions were developed for each attribute and are included in Appendix 1, along with at least three citations of illustrative studies collected in the literature review for the highest tier of each nested attribute added to the SES framework. Listed citations for each attribute are not presented as definitive authoritative sources nor as a comprehensive listing of all studies in which the attribute was identified. Rather, they represent examples of how scholars have applied the concept in other studies.

RESULTS

The SES framework organizes system attributes into nested tiers. The first-tier attributes of the SES framework, as defined for an urban stormwater management system, are summarized in Fig. 2.

Table 1. Modified second- through fifth-tier attributes of the urban stormwater social-ecological system (SES) framework. Factors modified from McGinnis and Ostrom (2014), Epstein et al. (2013), and Vogt et al. (2015) that are specific for green infrastructure adoption in urban stormwater social-ecological systems are noted with italic font.

Social, economic, and political settings (S)	Ecological rules (ER)	Governance systems (GS)	Actors (A)	Resource systems (RS)	Resource units (RU)	Related ecosystems (ECO)	Interactions (I)	Outcome criteria (O)
S1 - Economic development	ER1 - Physical rules	GS1 - Policy area	A1 - Number of actors	RS1 - Sector	RU1 - Resource unit	ECO1 - Climate patterns	I1 - Harvesting	O1 - Social performance measures
S2 - Demographic trends	ER2 - Chemical rules	GS2 - Geographical scale	A2 - Socioeconomic attributes	RS2 - Clarity of system boundaries	RU2 - Resource unit mobility	ECO2 - Pollution patterns	I2 - Information sharing	O2 - Ecological performance measures
S3 - Political stability	ER3 - Biological rules	GS3 - Population	A3 - History or past experiences	RS3 - Size of resource system	RU3 - Growth or replacement rate	ECO3 - Flows into and out of focal SES	I3 - Deliberation processes	O3 - Externalities to other SESs
S4 - Government policies	ER4 - Biological rules	GS4 - Regime type	A4 - <i>Experimentation</i>	RS4 - Human-constructed facilities	RU4 - Interaction among resource units		I4 - Conflicts	
S5 - Market incentives		GS5 - Rule-making organizations	A5 - <i>Environmental injustices</i>	RS5 - Human-constructed facilities	RU5 - Economic value		I5 - Investment activities	
S6 - Media organization		GS5.1 - <i>Number of organizations</i>	A6 - Location	RS6 - <i>Locations</i>	RU6 - Number of units		I6 - Lobbying activities	
S7 - Technology		GS5.2 - <i>Institutional diversity</i>	A7 - Leadership/ entrepreneurship	RS7 - <i>Availability for potential facilities</i>	RU7 - Distinctive characteristics		I7 - Self-organizing activities	
		GS5.3 - <i>Economic resources</i>	A8 - <i>Policy entrepreneur</i>	RS8 - <i>Functionality</i>	RU8 - Spatial and temporal distribution		I8 - Productivity of system	
		GS5.4 - <i>Human resources</i>	A9 - Norms (trust-reciprocity)/ social capital	RS9 - Equilibrium properties			I9 - Networking activities	
		GS6 - Rules-in-use	A10 - <i>Trust</i>	RS10 - <i>Frequency/timing of disturbances</i>			I10 - Monitoring activities	
		GS6.1 - Operational-choice rules	A11 - <i>Reciprocity</i>	RS11 - Predictability of system dynamics			I11 - Evaluative activities	
		GS6.1.1 - Stormwater ordinances	A12 - <i>Social capital</i>	RS12 - Storage characteristics				
		GS6.1.1.1 - Technical basis	A13 - Knowledge of SES/mental models	RS13 - <i>Soil characteristics</i>				
		GS6.1.1.2 - Administrative apparatus	A14 - <i>Types of knowledge</i>	RS14 - <i>Imperviousness</i>				
		GS6.1.1.3 - Enforcement provisions	A15 - <i>Traditional ecological knowledge</i>	RS15 - Location				
		GS6.1.2 - Stormwater utility funding scheme	A16 - <i>Local ecological knowledge</i>	RS16 - Ecological history				
		GS6.1.2.1 - Price instrument	A17 - <i>Technical expertise</i>	RS17 - <i>Human use and disturbance</i>				
		GS6.1.2.2 - Credits or fee reduction	A18 - <i>Mechanisms to share knowledge</i>					
		GS6.1.3 - Stormwater management plans	A19 - <i>Scale of mental models</i>					
		GS6.1.3.1 - Operations and maintenance	A20 - Importance of resource (dependence)					
		GS6.1.4 - Related regulations	A21 - Technology available					
		GS6.2 - Collective-choice rules	A22 - <i>Ownership</i>					
		GS6.3 - Constitutional-choice rules	A23 - <i>Research support</i>					
		GS7 - Property-rights systems	A24 - <i>Environmental performance</i>					
		GS7.1 - Stormwater management	A25 - <i>Stormwater management</i>					
		GS7.1.1 - Watercourse law	A26 - <i>Environmental "cobenefits"</i>					
		GS7.1.1.1 - Prior appropriation doctrine	A27 - <i>Social benefits</i>					
		GS8 - Repertoire of norms and strategies	A28 - <i>Design and complexity</i>					
		GS8.1 - Diversity	A29 - <i>Maintenance procedures</i>					
		GS8.2 - Risk tolerance	A30 - <i>Reliability</i>					
		GS9 - Network structure	A31 - <i>Associated costs</i>					
		GS9.1 - Horizontal	A32 - <i>Capital</i>					
		GS9.2 - Vertical	A33 - <i>Operation and maintenance</i>					
		GS10 - Historical continuity	A34 - <i>Perceptions/attitudes</i>					

The resource system (RS) is defined as an urban stormwater system; i.e., the system of water flows that results from wet weather. Multiple sets of resource units (RU) can be defined within an urban stormwater system, such as units of stormwater or the storage volumes available for stormwater throughout the

system. The governance system (GS) includes the sets of rules agreed upon by national, state, and local organizations for managing urban stormwater. The actors (A) category includes individuals and groups that interact with the urban stormwater system. Multiple categories of actors can be defined, including

individuals and groups that are involved in rule-making processes, and property owners that are affected by stormwater management decisions. Attributes from each of these categories provide inputs to action situations, where interactions (I) among actors transform these inputs into various outcomes, which can be measured by outcome criteria (O). Additional influences flow between the focal SES attributes and related ecosystems (ECO); ecological rules (ER); and social, economic, and political settings (S).

Fig. 2. First tiers of social-ecological system framework for an urban stormwater social-ecological system (adapted from Ostrom [2007] and Epstein et al. [2013]).

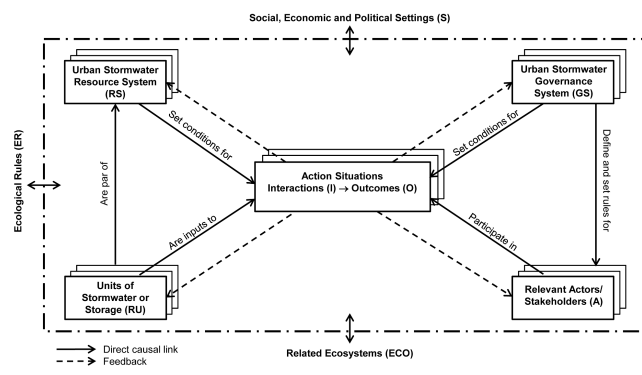


Table 1 summarizes the changes made to the SES framework. A detailed summary of the modifications, along with working definitions and illustrative references, are provided in Appendix 1. Because the study focus is only on changes related to resource management programs, the findings led to detailed expansions of multiple governance system and actor attributes. Attributes for RU, ECO, ER, and S were not modified beyond second-tier changes suggested by McGinnis and Ostrom et al. (2014) and Vogt et al. (2015), though many of these attributes have direct and important effects on the design of municipal stormwater management programs. Additional studies on implementing various technological designs may result in a more detailed account for influential attributes in these categories.

Multiple third-, fourth-, and fifth-tier variables were added to describe various attributes of stormwater management technologies that are available to actors within the SES (A9), such as research support (A9.2), associated costs (A9.3), and perceptions of particular technologies (A9.4). The addition of third-, fourth-, and fifth-tier variables related to human-constructed facilities (RS4) designates both the types and functionalities of existing and potential stormwater infrastructure. A notable factor related to the construction of GI technologies is the availability of suitable locations for potential facilities (RS4.1.1), which is often associated with other factors such as local soil characteristics (RS8.1) (Shuster et al. 2014). Additional tiers allow for a detailed account of the assortment of resources and rules used by organizations to manage GI technologies. Stormwater ordinances (GS6.1.1) often acted as a barrier to GI implementation (Nowacek et al. 2003, Lassiter 2007, Stockwell 2009, Dochow 2013). Another common barrier was lack of sufficient program funding (Clean Water America Alliance 2011, Siglin 2012, Winz et al. 2014), which is associated with limited

economic resources available to rule-making organizations (GS5.3), type of stormwater utility funding schemes (GS6.1.2), and socioeconomic attributes of actors (A2). Multiple attributes of actors that interact with and manage stormwater resources were found to influence GI program adoption, such as the leadership efforts of policy entrepreneurs (A5) and policy communities (A5.2), multiple actor knowledge types (A7.1), experimentation (i.e., technology pilot projects) (A3.1), and environmental injustices (A3.2).

DISCUSSION

In the broadest sense, integration of GI into an urban stormwater management system can be understood as the development of human-constructed facilities (RS4) across diffuse locations (RS4.1) using available technologies (A9) to alter the storage characteristics of an urban stormwater system (RS8). In developing this SES framework, additional third-, fourth-, and fifth-tier variables were needed to account for complex arrangements of social and biophysical factors that affect GI implementation. Operational-choice rules (GS6.1), such as ordinances, funding schemes, and comprehensive management plans, were found to be among the most complex factors. These rules are often further complicated by related SES regulations (GS6.1.4), such as zoning, building codes, and demolition practices (Lassiter 2007, Carter and Fowler 2008, Shuster et al. 2014). These related regulations are often managed by separate organizations, which may create barriers to GI implementation if the regulations are prohibitive. Property-rights systems that include prior-appropriation doctrines (GS7.1.1) can limit the choices of GI technologies (e.g., rainwater collection systems for some communities in the western United States) (Jensen 2008, Salkin 2009).

Funding was found to be among the most frequently cited barriers to GI (Godwin et al. 2008, Roy et al. 2008, Brown et al. 2009, Earles et al. 2009, Ruppert and Clark 2009, Stockwell 2009, Clean Water America Alliance 2011), most often in reference to the limited economic resources of enforcement organizations (GS5.1.1.2) and a lack of information on the cost-effectiveness of GI (A9.3). In the studies reviewed, stormwater management programs were enforced primarily by public organizations that selected stormwater management technologies to meet outcome criteria in a cost-effective manner. Environmental services associated with GI (A9.2.1.2), such as reducing urban heat island effects or promoting recreational opportunities, were cited as drivers for adoption when these benefits were quantifiable (Nowacek et al. 2003, Madden 2010). This suggests that it is difficult to maintain clear institutional boundaries when assessing the market and nonmarket value of GI because there may be additional benefits that GI can bring to a community beyond stormwater management.

The financial concerns of enforcement organizations are complicated by the design of effective stormwater utility funding schemes (GS6.1.2). Many funding schemes are predicated on the extent of total impervious area of urban land parcels because this metric has frequently been used to predict levels of surface water impairments due to stormwater runoff (Booth and Jackson 1997, Parikh et al. 2005). However, studies suggest that the subset of impervious surfaces that route runoff directly to surface waters via sewer pipes, known as directly connected impervious area or effective impervious area, may be responsible for most surface

water impairments due to urbanization (Brabec et al. 2002, Walsh 2004, Walsh et al. 2005, Roy and Shuster 2009). Thus, stormwater utility funding schemes based on total impervious area rather than effective impervious area may not lead to desired SES outcomes. Additional limitations of utility funding schemes may develop if financial credits for GI are calculated as a one-time credit based on the initial installation without including ongoing performance and maintenance criteria, or if residential property owners are not included in financial incentive programs (Parikh et al. 2005).

Technological attributes are described in both the social and ecological domains of the SES framework. While it has been argued that there is no need to create a separate technological domain (McGinnis and Ostrom 2014), we demonstrate a need to more fully develop robust descriptions of technological attributes within urban stormwater SESs because these attributes act as key feedback mechanisms between the social and ecological domains. Historically, technological innovations in urban water SESs have been shown to bring about desired social and ecological regime shifts, such as a reduction in water-borne illness and a decrease in the frequency of algal blooms due to eutrophic states of receiving waters (Melosi 1999, Smith et al. 1999). Urban water infrastructure choices may also lead to unforeseen consequences over long periods. For example, combined sewer systems were once deemed to be the most appropriate choice for urban settings due to factors such as cost-effectiveness and availability of water courses for overflow disposal (Tarr 1979). These decisions have left a legacy of water pollution problems for many communities, as combined sewer overflows continue to impair surface waters and create human health hazards (USEPA 2004, Donovan et al. 2008, Gooré Bi et al. 2015). By developing a comprehensive categorization of technological attributes within an SES framework, policy-makers will be better equipped to make well-informed decisions concerning technology selection for desired urban water SES outcomes.

Though additional characterizations were not added within several second-tier categories, such as resource units (RU) and outcome criteria (O), attributes in these categories have important implications for stormwater management technology decisions. For instance, stormwater management plans are traditionally designed according to the spatial and temporal distribution of stormwater flows in an urban area (RU7), which will be affected by changes in local precipitation patterns (RU2). The spatial and temporal distribution of stormwater volumes within an urban setting places clear boundaries on which technologies should be considered and where they should be situated in an urban setting (Askarizadeh et al. 2015). Additionally, the criteria used to select stormwater management technologies, such as relative cost-effectiveness or ecological performance measures, will often strongly influence enforcement officials' decision-making processes (Flynn et al. 2014). Expansion of these attribute categories may be necessary when considering research questions related to the design of specific stormwater technologies or the influence of particular outcome criteria.

Some limitations of the modified framework attributes should be noted. Because several programs reviewed in the literature are in early phases of development, some SES framework attributes are likely relevant to only nascent GI implementation. However, an analysis of GI technologies in urban stormwater SESs over longer

timescales may result in other variables having a greater effect (Brown et al. 2013). Much of the research we reviewed relies on case study methods such as the solicitation of particular actors' perceptions. Thus, some factors listed may pertain to specific actors or institutions, such as engineering firms, municipal officials, developers, or community residents. Additional studies can provide further insights into the possibility of shared, complementary interactions among actors within specific situations that result in the development of successful GI programs. It is also important to note that while the literature review was not restricted to studies from particular geographic locations, most studies were based in the United States or Australia, which prescribe similar stormwater governance structures. Researchers who use the revised SES framework in studies of community-based stormwater governance regimes may need to add more detailed characterizations of particular attributes (such as property-rights systems or collective-choice rules), or may need to omit others (such as particular operational rules).

CONCLUSION

We developed a modified SES framework to recognize the combinations of influential variables related to the development of municipal urban stormwater management programs that feature extensive use of GI technologies. The modifications made to the SES framework revealed the need for additional attribute tiers related to variables such as available technologies, actor characterizations, and operational-choice rules. Our findings demonstrate that affecting change in the built structure of urban stormwater systems involves multiple interacting attributes of the actors and governance systems within an SES.

The framework we developed should be interpreted as a flexible, proposed framework rather than a definitive set of variables that will be relevant in all urban stormwater SES cases. Other studies highlight qualities of particular attributes within adapted SES frameworks to explore dynamic interactions and outcomes of interest (Fleischman et al. 2010, Basurto et al. 2013, Nagendra and Ostrom 2014, Leslie et al. 2015, Partelow and Boda 2015). The revised framework we presented highlights key factors of GI adoption that can be further explored using various theories and models to assess outcomes of interest related to urban stormwater SESs seeking to adopt GI technologies (Flynn et al. 2014). Tiers may be added or omitted to accommodate particular theories and research questions.

There is a need to explore the specific, contextual factors affecting the decision to adopt particular management approaches in urban stormwater SESs. The growing popularity of GI systems across municipalities carries a risk that these technologies will be perceived as a panacea for stormwater management (Ostrom 2007). However, there continues to be a need for a more sophisticated quantitative understanding of how GI technologies bring out particular SES outcomes. Neither a fully green nor entirely gray infrastructure approach to stormwater management will likely be optimal at any location. Instead, long-term solutions must be built around improved knowledge of factors influencing water quantity and quality in urban areas, and leveraging the services and capacities of both gray and green infrastructure. Such understanding should include the consideration of the unique characteristics of a particular urban water SES.

Responses to this article can be read online at:
<http://www.ecologyandsociety.org/issues/responses.php/8756>

Acknowledgments:

This work was supported in part by NSF grant #1444755, Urban Resilience to Extremes Sustainability Research Network. We also thank the SURDNA Foundation for providing funding for part of this work. We are grateful for the helpful feedback from Dr. Burnell Fischer, Dr. Jessica Vogt, and colleagues at The Vincent and Elinor Ostrom Workshop in Political Theory and Policy Analysis at Indiana University, Bloomington, Indiana. We are also indebted to the work of Elinor Ostrom.

LITERATURE CITED

- Altheide, D., M. Coyle, K. DeVriese, and C. Schneide. 2008. Emergent qualitative document analysis. Pages 127–151 in S. N. Hesse-Biber, and P. Leavy, editors. *Handbook of emergent methods*. Guilford Press, New York, USA.
- Askarizadeh, A., M. A. Rippey, T. D. Fletcher, D. L. Feldman, J. Peng, P. Bowler, A. S. Mehring, B. K. Winfrey, J. A. Vrugt, A. AghaKouchak, S. C. Jiang, B. F. Sanders, L. A. Levin, S. Taylor, and S. B. Grant. 2015. From rain tanks to catchments: use of low-impact development to address hydrologic symptoms of the urban stream syndrome. *Environmental Science & Technology* 49 (19):11264–11280. <http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01635> <http://dx.doi.org/10.1021/acs.est.5b01635>
- Basurto, X., S. Gelcich, and E. Ostrom. 2013. The social-ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change* 23 (6):1366–1380. <http://dx.doi.org/10.1016/j.gloenvcha.2013.08.001>
- Berkes, F., C. Folke, and J. Colding. 1998. *Linking social and ecological systems: management practices and social mechanisms for building resilience*. Cambridge University Press, Cambridge, UK.
- Binder, C. R., J. Hinkel, P. W. G. Bots, and C. Pahl-Wostl. 2013. Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society* 18(4):26. <http://dx.doi.org/10.5751/ES-05551-180426>
- Booth, D. B., and C. R. Jackson. 1997. Urbanization of aquatic systems: degradation thresholds, stormwater detection, and the limits of mitigation. *Journal of the American Water Resources Association* 33(5):1077–1090. <http://dx.doi.org/10.1111/j.1752-1688.1997.tb04126.x>
- Brabec, E., S. Schulte, and P. L. Richards. 2002. Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *Journal of Planning Literature* 16(4):499–514. <http://dx.doi.org/10.1177/088541202400903563>
- Brown, R., M. Farrelly, and N. Keath. 2009. Practitioner perceptions of social and institutional barriers to advancing a diverse water source approach in Australia. *Water Resources Development* 25(1):15–28. <http://dx.doi.org/10.1080/07900620802586090>
- Brown, R. R., M. A. Farrelly, and D. A. Loorbach. 2013. Actors working the institutions in sustainability transitions: the case of Melbourne's stormwater management. *Global Environmental Change* 23(4):701–718. <http://dx.doi.org/10.1016/j.gloenvcha.2013.02.013>
- Carter, T., and L. Fowler. 2008. Establishing green roof infrastructure through environmental policy instruments. *Environmental Management* 42:151–164. <http://dx.doi.org/10.1007/s00267-008-9095-5>
- Cinner, J. E., T. R. McClanahan, M. A. MacNeil, N. A. J. Graham, T. M. Daw, A. Mukminin, D. A. Feary, A. L. Rabearisoa, A. Wamukota, N. Jiddawi, S. J. Campbell, A. H. Baird, F. A. Januchowski-Hartley, S. Hamed, R. Lahari, T. Morove, and J. Kuange. 2012. Comanagement of coral reef social-ecological systems. *Proceedings of the National Academy of Sciences of the United States of America* 109(14):5219–5222. <http://dx.doi.org/10.1073/pnas.1121215109>
- Clean Water America Alliance. 2011. *Barriers and gateways to green infrastructure*. Washington, D.C., USA. [online] URL: <http://uswateralliance.org/sites/uswateralliance.org/files/publications/Barriers-and-Gateways-to-Green-Infrastructure.pdf>
- Coles, J. F., G. McMahon, A. H. Bell, L. R. Brown, F. A. Fitzpatrick, B. S. Eikenberry, M. D. Woodside, T. F. Cuffney, W. L. Bryant, K. Capiella, L. Fraley-McNeal, and W. P. Stack. 2012. Effects of urban development on stream ecosystems in nine metropolitan study areas across the United States. *U.S. Geological Survey Circular* 1373. [online] URL: <http://pubs.usgs.gov/circ/1373/pdf/Circular1373.pdf>
- De Sousa, M. R. C., F. A. Montalto, and S. Spatari. 2012. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. *Journal of Industrial Ecology* 16 (6):901–913. <http://dx.doi.org/10.1111/j.1530-9290.2012.00534.x>
- Dochow, D. 2013. *Transforming tradition: a case study of stormwater management in Clark County, Washington to assess barriers to low impact development strategies*. Thesis. Evergreen State College, Olympia, Washington, U.S.A. [online] URL: http://archives.evergreen.edu/masterstheses/Accession86-10MES/Dochow_D2013.pdf
- Dominguez, D., B. Truffer, and W. Gujer. 2011. Tackling uncertainties in infrastructure sectors through strategic planning: the contribution of discursive approaches in the urban water sector. *Water Policy* 13(3):299–316. <http://dx.doi.org/10.2166/wp.2010.109>
- Donovan, E., K. Unice, J. D. Roberts, M. Harris, and B. Finley. 2008. Risk of gastrointestinal disease associated with exposure to pathogens in the water of the Lower Passaic River. *Applied and Environmental Microbiology* 74:994–1003. <http://dx.doi.org/10.1128/AEM.00601-07>
- Earles, A., D. Rapp, J. Clary, and J. Lopitz. 2009. Breaking down the barriers to low impact development in Colorado. Pages 1–10 in S. Starrett, editor. *World Environmental and Water Resources Congress 2009: Great Rivers*, May 2009. [http://dx.doi.org/10.1061/41036\(342\)91](http://dx.doi.org/10.1061/41036(342)91)
- Epstein, G., J. M. Vogt, S. K. Mincey, M. Cox, and B. Fischer. 2013. Missing ecology: integrating ecological perspectives with

the social-ecological system framework. *International Journal of the Commons* 7(2):432–453. <http://dx.doi.org/10.18352/ijc.371>

Ferguson, B. C., R. R. Brown, and A. Deletic. 2013. Diagnosing transformative change in urban water systems: theories and frameworks. *Global Environmental Change* 23(1):264–280. <http://dx.doi.org/10.1016/j.gloenvcha.2012.07.008>

Fleischman, F., K. Boenning, G. A. Garcia-Lopez, S. Mincey, M. Schmitt-Harsh, K. Daedlow, M. C. Lopez, X. Basurto, B. Fischer, and E. Ostrom. 2010. Disturbance, response, and persistence in self-organized forested communities: analysis of robustness and resilience in five communities in southern Indiana. *Ecology and Society* 15(4):9. [online] URL: <http://www.ecologyandsociety.org/vol15/iss4/art9/>

Fletcher, T. D., W. Shuster, W. F. Hunt, R. Ashley, D. Butler, S. Arthur, S. Trowsdale, S. Barraud, A. Semadeni-Davies, J.-L. Bertrand-Krajewski, P. S. Mikkelsen, G. Rivard, M. Uhl, D. Dagenais, and M. Viklander. 2014. SUDS, LID, BMPs, WSUD and more – the evolution and application of terminology surrounding urban drainage. *Urban Water Journal* 12:1–18.

Flynn, C. D., C. I. Davidson, and J. Mahoney. 2014. Transformational changes associated with sustainable stormwater management practices in Onondaga County, New York. Pages 89–100 in J. Crittenden, C. Hendrickson, and B. Wallace, editors. *ICSI 2014: creating infrastructure for a sustainable world*. <http://ascelibrary.org/doi/abs/10.1061/9780784478745.009>

Godwin, D., B. L. Parry, F. A. Burris, S. S. Chan, and A. Punton. 2008. *Barriers and opportunities for low impact development: case studies from three Oregon communities*. Oregon State University, Corvallis, Oregon, USA. [online] URL: <http://seagrant.oregonstate.edu/sites/default/files/sgpubs/onlinepubs/w06002.pdf>

Gooré Bi, E., F. Monette, and J. Gasperi. 2015. Analysis of the influence of rainfall variables on urban effluents concentrations and fluxes in wet weather. *Journal of Hydrology* 523:320–332. <http://dx.doi.org/10.1016/j.jhydrol.2015.01.017>

Gutiérrez, N. L., R. Hilborn, and O. Defeo. 2011. Leadership, social capital and incentives promote successful fisheries. *Nature* 470(7334):386–389. <http://dx.doi.org/10.1038/nature09689>

Hatt, B. E., T. D. Fletcher, C. J. Walsh, and S. L. Taylor. 2004. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. *Environmental Management* 34:112–124. <http://dx.doi.org/10.1007/s00267-004-0221-8>

Holling, C. S., and L. H. Gunderson. 2002. *Panarchy: understanding transformations in human and natural systems*. Island Press, Washington D.C., USA.

Jensen, M. A. 2008. *Feasibility of rainwater harvesting for urban water management in Salt Lake City*. Thesis. University of Utah, Salt Lake City, Utah, USA. [online] URL: <http://content.lib.utah.edu/utis/getfile/collection/etd2/id/1406/filename/image>

Lassiter, R. 2007. *An assessment of impediments to low-impact development in the Virginia portion of the Chesapeake Bay watershed*. Thesis. Virginia Commonwealth University, Richmond, Virginia, USA. [online] URL: <http://scholarscompass.vcu.edu/cgi/viewcontent.cgi?article=1891&context=etd>

Leslie, H. M., X. Basurto, M. Nenadovic, L. Sievanen, K. C. Cavanaugh, J. J. Cota-Nieto, B. E. Erisman, E. Finkbeiner, G. Hinojosa-Arango, M. Moreno-Báez, and S. Nagavarapu, S. M. W. Reddy, A. Rodríguez, K. Siegel, J. J. Ulibarría-Valenzuela, A. Hudson Weaver, and O. Aburto-Oropeza. 2015. Operationalizing the social-ecological systems framework to assess sustainability. *Proceedings of the National Academy of Sciences of the United States of America* 112(19):5979–5984. <http://dx.doi.org/10.1073/pnas.1414640112>

Madden, S. A. 2010. *Choosing green over gray: Philadelphia's innovative stormwater infrastructure plan*. Thesis. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA. [online] URL: http://www.mit.edu/afs.new/athena/dept/cron/project/urban-sustainability/Stormwater_Sarah%20Madden/sarahmadden_thesis_MIT.pdf

Marshall, G. 2015. A social-ecological systems framework for food systems research: accommodating transformation systems and their products. *International Journal of the Commons* 9:881–908. <http://dx.doi.org/10.18352/ijc.587>

McGinnis, M. D., and E. Ostrom. 2014. Social-ecological framework: initial changes and continuing challenges. *Ecology and Society* 19(2):30. [online] URL: <http://dx.doi.org/10.5751/ES-06387-190230>

Melosi, M. V. 1999. *The sanitary city: urban infrastructure in American from colonial times to the present*. Johns Hopkins University Press, Baltimore, Maryland, USA.

Nagendra, H., and E. Ostrom. 2014. Applying the social-ecological system framework to the diagnosis of urban lake commons in Bangalore, India. *Ecology and Society* 19(2):67. <http://dx.doi.org/10.5751/ES-06582-190267>

National Research Council. 2009. *Urban stormwater management in the United States*. National Academies Press, Washington, D. C., USA [online] URL: <http://www.nap.edu/catalog/12465/urban-stormwater-management-in-the-united-states>

Novotny, V., J. Ahern, and P. Brown. 2010. *Water centric sustainable communities: planning, retrofitting and building the next urban environment*. John Wiley & Sons, Hoboken, New Jersey, USA. <http://dx.doi.org/10.1002/9780470949962>

Nowacek, D., E. Nelson, and J. Petchenik. 2003. *Social and institutional barriers to stormwater infiltration*. Wisconsin Department of Natural Resources-Bureau of Integrated Science Services. [online] URL: http://www.kitsaplid.org/resources/Barriers_to_SW_Infiltration.pdf

Ostrom, E. 2007. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America* 104(39):15181–15187. <http://dx.doi.org/10.1073/pnas.0702288104>

Ostrom, E. 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325 (5939):419–422. <http://dx.doi.org/10.1126/science.1172133>

Ostrom, E., M. Cox, and E. Schlager. 2014. An assessment of the institutional analysis and development framework. Pages 267–306 in P. A. Sabatier, and C. Weible, editors. *Theories of the Policy Process*. Third edition. Westview Press, Colorado, USA.

- Pahl-Wostl, C. 2007. Transitions towards adaptive management of water facing climate and global change. *Water Resources Management* 21(1):49–62. <http://dx.doi.org/10.1007/s11269-006-9040-4>
- Pahl-Wostl, C., G. Holtz, B. Kastens, and C. Knieper. 2010. Analyzing complex water governance regimes: the management and transition framework. *Environmental Science & Policy* 13(7):571–581. <http://dx.doi.org/10.1016/j.envsci.2010.08.006>
- Parikh, P., M. A. Taylor, T. Hoagland, H. Thurston, and W. Shuster. 2005. Application of market mechanisms and incentives to reduce stormwater runoff: an integrated hydrologic, economic and legal approach. *Environmental Science & Policy* 8(2):133–144. <http://dx.doi.org/10.1016/j.envsci.2005.01.002>
- Partelow, S., and C. Boda. 2015. A modified diagnostic social-ecological system framework for lobster fisheries: case implementation and sustainability assessment in Southern California. *Ocean & Coastal Management* 114:204–217. <http://dx.doi.org/10.1016/j.ocecoaman.2015.06.022>
- Pyke, C., M. P. Warren, T. Johnson, J. LaGro Jr., J. Scharfenberg, P. Groth, R. Freed, W. Schroeer, and E. Main. 2011. Assessment of low impact development for managing stormwater with changing precipitation due to climate change. *Landscape and Urban Planning* 103(2):166–173. <http://dx.doi.org/10.1016/j.landurbplan.2011.07.006>
- Roy, A. H., and W. D. Shuster. 2009. Assessing impervious surface connectivity and applications for watershed management. *Journal of the American Water Resources Association* 45(1):198–209. <http://dx.doi.org/10.1111/j.1752-1688.2008.00271.x>
- Roy, A. H., S. J. Wenger, T. D. Fletcher, C. J. Walsh, A. R. Ladson, W. D. Shuster, H. W. Thurston, and R. R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental Management* 42(2):344–359. <http://dx.doi.org/10.1007/s00267-008-9119-1>
- Ruppert, T., and M. Clark. 2009. Understanding and overcoming legal and administrative barriers to LID: a Florida case study. Pages 1–10 in N. She and M. Char, editors. *Low impact development for urban ecosystem and habitat protection*. International Low Impact Development Conference 2008, Seattle, Washington, USA, November 16–19, 2008. [http://dx.doi.org/10.1061/41009\(333\)50](http://dx.doi.org/10.1061/41009(333)50)
- Salkin, P. E. 2009. Sustainability and land use planning: greening state and local land use plans and regulations to address climate change challenges and preserve resources for future generations. *William and Mary Environmental Law and Policy Review* 34:121.
- Shuster, W. D., S. Dadio, P. Drohan, R. Losco, and J. Shaffer. 2014. Residential demolition and its impact on vacant lot hydrology: implications for the management of stormwater and sewer system overflows. *Landscape and Urban Planning* 125:48–56. <http://dx.doi.org/10.1016/j.landurbplan.2014.02.003>
- Shuster, W. D., and A. S. Garmestani. 2015. Adaptive exchange of capitals in urban water resources management: an approach to sustainability? *Clean Technologies and Environmental Policy* 17(6):1393–1400. <http://dx.doi.org/10.1007/s10098-014-0886-5>
- Siglin, D. D. 2012. *Municipal use of green stormwater infrastructure in the Delaware River Basin: barriers, drivers, and opportunities for implementation*. Thesis. Pennsylvania State University, Pennsylvania, USA. [online] URL: <https://etda.libraries.psu.edu/paper/15290/12231>
- Smith, V. H., G. D. Tilman, and J. C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution* 100:179–196. [http://dx.doi.org/10.1016/S0269-7491\(99\)00091-3](http://dx.doi.org/10.1016/S0269-7491(99)00091-3)
- Stockwell, A. 2009. *Analysis of barriers to low impact development in the North Coast Redwood Region, California*. Thesis. Humboldt State University, Arcata, California, USA. [online] URL: http://humboldt-dspace.calstate.edu/bitstream/handle/2148/595/stockwell_thesis_2.12.10_FINAL2.pdf?sequence=1
- Tarr, J. A. 1979. The separate vs. combined sewer problem: a case study in urban technology design choice. *Journal of Urban History* 5(3):308–339.
- Tzoulas, K., K. Korpela, S. Venn, V. Yli-Pelkonen, A. Kaźmierczak, J. Niemela, and P. James. 2007. Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. *Landscape and Urban Planning* 81(3):167–178. <http://dx.doi.org/10.1016/j.landurbplan.2007.02.001>
- United States Environmental Protection Agency (USEPA). 2004. Report to Congress: impacts and control of CSOs and SSOs. No. EPA 833-R-04-001.
- Villarreal, E. L., A. Semadeni-Davies, and L. Bengtsson. 2004. Inner city stormwater control using a combination of best management practices. *Ecological Engineering* 22:279–298. <http://dx.doi.org/10.1016/j.ecoleng.2004.06.007>
- Vogt, J. M., G. B. Epstein, S. K. Mincey, B. C. Fischer, and P. McCord. 2015. Putting the “E” in SES: unpacking the ecology in the Ostrom social-ecological system framework. *Ecology and Society* 20(1):55. <http://dx.doi.org/10.5751/ES-07239-200155>
- Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecology and Society* 9(2):5. [online] URL: <http://www.ecologyandsociety.org/vol9/iss2/art5/>
- Walsh, C. J. 2004. Protection of in-stream biota from urban impacts: minimise catchment imperviousness or improve drainage design? *Marine & Freshwater Research* 55(3):317–326. <http://dx.doi.org/10.1071/mf03206>
- Walsh, C. J., T. D. Fletcher, and A. R. Ladson. 2005. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society* 24(3):690–705. <http://dx.doi.org/10.1899/04-020.1>
- Wendel, H. E. W., J. A. Downs, and J. R. Mihelcic. 2011. Assessing equitable access to urban green space: the role of engineered water infrastructure. *Environmental Science & Technology* 45:6728–6734. <http://dx.doi.org/10.1021/es103949f>
- Wiek, A., and K. L. Larson. 2012. Water, people, and sustainability—a systems framework for analyzing and assessing water governance regimes. *Water Resource Management* 26(11):3153–3171. <http://dx.doi.org/10.1007/s11269-012-0065-6>
- Winz, I., S. Trowsdale, and G. Brierley. 2014. Understanding barrier interactions to support the implementation of sustainable urban water management. *Urban Water Journal* 11(6):497–505. <http://dx.doi.org/10.1080/1573062x.2013.832777>

APPENDIX 1. Modified social-ecological system framework for urban stormwater systems with working definitions and references. Supplemental Information

Table 1: Modified framework for green infrastructure adoption in urban stormwater social-ecological systems. References provided as working definitions and illustrative examples from the literature.

Tier Level	Attribute	Working Definition	Definition References [†] , and Select Illustrative Examples [‡]
Se- cond Th- ird Fo- ur- Fifth th			
	Ecological Rules (ER)	The broader context of laws, theories, and principles developed in the natural sciences	Epstein et al. (2013) [†]
ER1	Physical rules	Laws, theories, and principles of or relating to nature and properties of matter and energy	
ER2	Chemical rules	Laws, theories, and principles of or relating to composition, structure, properties, and change of matter	
ER3	Biological rules	Laws, theories, and principles of or relating to living organisms	
	Social, economic, and political settings (S)	The broader context within which the governance system per se is located, including the effects of market dynamics and cultural change	McGinnis (2011) [†]
S1	Economic development	Efforts that seek to improve the economic well-being and quality of life for a community	Madden (2010) [‡] , Winz et al. (2014) [‡]
S2	Demographic trends	Developments and changes in human populations	Travaline et al. (2015) [‡]
S3	Political stability	Degree of durability and integrity of a current government regime	
S4	Government policies	Sets forth policies that address public issues related to, or otherwise effect, stormwater flows	Roy et al. (2008) [‡] , Dunn (2010) [‡] , Dochow (2013) [‡] , Holloway et al. (2014) [‡]
S5	Market incentives	Policies that incentivize certain stormwater management approaches	Carter and Fowler (2008) [‡] , Dunn (2010) [‡] , Clean Water America Alliance (2011) [‡] , Dochow (2013) [‡]
S6	Media organization	Characteristics of entities engaged in disseminating information to the general public through mass communication channels	Madden (2010) [‡] , Cettner et al. (2014) ^b
S7	Technology	Broader cultural settings and development context that affect the technologies regularly used by actors in their interactions with the resource units	Clean Water America Alliance (2011) [‡] , Siglin (2012) [‡] , Cettner et al. (2014b) [‡]

(con'd)

Resource Units (RU)		Characteristics of the units extracted from a resource system, which can then be consumed or used as an input in production or exchanged for other goods or services.	McGinnis (2011) [†]
R-U1	Resource unit mobility	Ability for resource units to move throughout the resource system	
R-U2	Growth or replacement rate	Absolute or relative descriptions of changes in quantities (x) of resource units over time (t)	Basurto et al. (2013) [†] , Clean Water America Alliance (2011) [‡]
R-U3	Interaction among resource units	Interactions among resource units during different time periods affecting the future structure of the population	Basurto et al. (2013) [†]
R-U4	Economic value	Value of resource units in relation to the portfolio of resources available to actors	Basurto et al. (2013) [†] , Clean Water America Alliance (2011) [‡]
R-U5	Number of units	Amount of individual resource units in resource system	
R-U6	Distinctive markings	Characteristics that can be identified in resource units and affect actors' behavior toward them	Basurto et al. (2013) [†]
R-U7	Spatial and temporal distribution	Allocation patterns of resource units across a geographic area in a particular time period	Basurto et al. (2013) [†]
Resource systems (RS)		The biophysical system from which resource units are extracted and through which the levels of the focal resource are regenerated by natural dynamic processes	McGinnis (2011) [†]
RS1	Sector	Characteristic(s) of a resource system that distinguishes it from other resource systems	Ostrom (2007) [†]
RS2	Clarity of system boundaries	Biophysical characteristics that make feasible for actors to determine where the resource system starts or ends	Basurto et al. (2013) [†]
RS3	Size of resource system	Absolute or relative descriptions of the spatial extent of a resource system	Basurto et al. (2013) [†]
RS4	Human-constructed facilities	Facilities produced by actors that affect the resource system	
RS-4.1	Locations	Spatial extent where facilities are constructed by actors	Perez-Pedini et al. (2005) [‡] , Montalto et al. (2013) [‡] , Askarizadeh et al. (2015) [‡]
R-S4-1.1	Potential facilities	Availability of suitable locations for potential facilities	Clean Water America Alliance (2011) [‡] , Hammitt (2010) [‡] , Shuster et al. (2014) [‡]
RS-4.2	Functionality	Degree to which stormwater management facilities achieve desired outcomes	Nowacek et al. (2003) [‡] , Siglin (2012) [‡] , Keeley et al. (2013) [‡] , Flynn et al. (2014) [‡]

(con'd)

RS5	Productivity of system	Rate of generation of resource units	Clean Water America Alliance (2011) [‡] , Askarizadeh et al. (2015) [‡]
RS6	Equilibrium properties	Characterization of the type of attractor of a resource system along a range from one to multiple (chaotic) attractors	
RS-6.3	Frequency/timing of disturbances	Characterization of extreme events (e.g., intense wet weather events)	Madden (2010) [‡] , Clean Water America Alliance (2011) [‡] , Keeley et al. (2013) [‡] , Cettner et al. (2014a) [‡]
RS7	Predictability of system dynamics	Degree to which actors are able to forecast or identify patterns in environmentally driven variability on recruitment	Basurto et al. (2013) [†] , Askarizadeh et al. (2015) [‡]
RS8	Storage characteristics	Degree to which the resource units can be retained or detained	
RS-8.1	Soil characteristics	Hydrologic characteristics of soils	Nowacek et al. (2003) [‡] , Clean Water America Alliance (2011) [‡] , Shuster et al. (2014) [‡] , Rhea et al. (2014) [‡]
RS-8.2	Impervious surface area	Amount of system coverage by materials that inhibit water infiltration	Dietz and Clausen (2008) [‡] , Roy and Shuster (2009) [‡] , Kertesz et al. (2014) [‡]
RS9	Location	Spatial and temporal extent where resource units are found by actors	Hammitt (2010) [‡] , Madden (2010) [‡] , Askarizadeh et al. (2015) [‡]
RS-10	Ecosystem history	Past interactions that affect current actors' behaviors and stormwater management plans	
RS-10.3	Human use and disturbance	Past interactions in which actors have greatly degraded resource system quality	Shandas and Messer, (2008) [‡] , Hammitt (2010) [‡] , Madden (2010) [‡] , Flynn et al. (2014) [‡]
Governance systems (GS)		The prevailing set of processes or institutions through which the rules shaping the behavior of the actors are set and revised	McGinnis (2011) [†]
GS1	Policy area	Rule systems tailored for a particular area of knowledge, geography, or time	Basurto et al. (2013) [†] , Holloway et al. (2014) [‡]
GS2	Geographical scale of governance system	Defined area that participates in, or is subject to, the system of governance	McGinnis and Ostrom (2014) [†] , Nowacek et al. (2003) [‡] , Siglin (2012) [‡] , Stockwell (2009) [‡]

(con'd)

GS3	Population	Defined group of people that participates in, or is subject to, the system of governance	McGinnis and Ostrom (2014) [†]
GS4	Regime type	Specifies the logic upon which the overarching governance system is organized	McGinnis and Ostrom (2014) [†]
GS5	Rule-making organizations	Institutions recognized by external actors and/or authorities that facilitate formal structured interactions among actors affected by these institutions	McGinnis and Ostrom (2014) [†]
G-S5.1	Number of organizations	Number of organizations affecting decision-making processes related to stormwater management in the watershed	Madden (2010) [‡] , (Shuster et al., 2008) [‡] Hammitt (2010) [‡] , Keeley et al. (2013) [‡]
G-S5.2	Institutional diversity	Degree of variation represented among rule-making organizations (including public sector, private sector, nongovernmental, community-based, or hybrid organizations)	Stockwell (2009) [‡] , Hammitt (2010) [‡] , Keeley et al. (2013) [‡]
G-S5.3	Economic resources	Funds available to an organization that are used for the creation, operation and maintenance of the stormwater management program. Funds may be generated through a variety of means such as a variety of taxes, service charges, exactions, assessments, grants, loans, and bonds.	Debo and Reese (2003) [†] , (Clean Water America Alliance (2011) [‡] , Keeley et al. (2013) [‡]
G-S5.4	Human resources	Human capital available to an organization for the creation, operation and maintenance of the stormwater management program.	Roy et al. (2008) [‡] , Stockwell (2009) [‡] , Winz et al. (2014) [‡]
GS6	Rules-in-use	Regulations or principles that specify the values of the working components of an action situation, each of which has emerged as the outcome of interactions in an adjacent action situation at a different level of analysis or arena of choice.	Ostrom et al. (1994) [†] , Clean Water America Alliance (2011) [‡] , Winz et al. (2014) [‡]
G-S6.1	Operational-choice rules	Set of regulations or principles governing the implementation of practical decisions by individuals authorized or allowed to take these actions, often as a result of collective choice processes	McGinnis (2011) [†] , Hammitt (2010) [‡]
G-S6-.1.1	Stormwater ordinances and regulations	Sets forth public policies directly related to drainage, flood control, and water quality aspects of stormwater, as well as the legal framework for permitting implementation of the controls.	Debo and Reese (2003) [†] , Hammitt (2010) [‡] , Madden (2010) [‡] , Siglin (2012) [‡]
GS6-.1.1.1	Technical basis	Performance standards, design criteria and information provided by rule-making organizations to assist designers in complying with ordinances and regulations.	Debo and Reese (2003) [†] , Roy et al. (2008) [‡] , Hammitt (2010) [‡] , Dochow (2013) [‡]
GS6-.1.1.2	Administrative apparatus	Required procedures, such as approvals, permits, and inspections, to ensure that measures meet technical and legal requirements	Debo and Reese (2003) [†] , Jaffe et al. (2010) [‡] , Kulkarni, (2012) [‡] , Dochow (2013) [‡]

GS6.- 1.1.3	Enforcement provisions	Procedures for penalties (such as sanctions) applied to rule violators	Dunn (2010) [‡] , Hammitt (2010) [‡] , Jaffe et al. (2010) [‡]
G- S6- .1.2	Stormwater utility funding scheme	Premise that urban drainage systems are public systems	Debo and Reese (2003) [†] , (Fletcher et al., 2011) [‡] , Keeley et al. (2013) [‡]
GS6.- 1.2.1	Price instrument	Fee or tax collected from ratepayers (e.g., property owners) in exchange for demand placed on stormwater system. May exist as a stormwater user fee or runoff charge.	Debo and Reese (2003) [†] , (Thurston et al., 2003) [‡] , Parikh et al. (2005) [†] , Hammitt (2010) [‡]
GS6.- 1.2.2	Credits or fee reductions	Mechanism to reduce utility fees. Can be derived through several bases, including the class of property, location within watershed, or activities on the property that reduce stormwater impacts.	Debo and Reese (2003) [†] , Carter and Fowler (2008) [‡] , (Thurston et al., 2010) [‡] , Kertesz et al. (2014) [‡]
G- S6- .1.3	Stormwater management plans	Comprehensive management plan outlining regulations, outcome criteria, technical approaches, financing strategies, and engineering design manuals	Madden (2010) [‡] , Kulkarni, (2012) [‡] , Keeley et al. (2013) [‡]
GS6.- 1.3.1	Operation and maintenance procedures	Specifies responsibilities, objectives, standards, approaches, and protocols related to the operation and maintenance of stormwater management infrastructure	Nowacek et al. (2003) [‡] , Clean Water America Alliance (2011) [‡] , Montalto et al. (2013) [‡]
G- S6- .1.4	Related regulations	Sets forth public policies that affect the implementation of decisions related to stormwater management (e.g., zoning codes, building codes).	Lassiter (2007) [‡] , Carter and Fowler (2008) [‡] , Hammitt (2010) [‡]
G- S6.2	Collective-choice rules	Set of regulations or principles governing institution creation and policy decision-making by actors who are authorized (or allowed) to do so, often as a result of constitutional-choice processes	McGinnis (2011) [†]
G- S6.3	Constitutional-choice rules	Set of regulations or principles governing the processes through which collective-choice stormwater management procedures are defined and legitimized, often resulting in a state or federal guideline or law	McGinnis (2011) [†] , Dunn (2010) [‡] , Winz et al. (2014) [‡]
GS7	Property-rights systems	Systems of interrelated rights that determine which actors have been authorized to carry out which actions with respect to a specified good or service	McGinnis (2011) [†]
G- S7.1	Watercourse law	Water laws pertaining to water within a defined watercourse	Debo and Reese (2003) [†] , Holloway et al. (2014) [‡]
G- S7- .1.1	Prior appropriation doctrine	Private water laws that are established by the date when beneficial uses were first initiated and tied to place and type of use, not location.	Debo and Reese (2003) [†] , Jensen (2008) [‡] , LaBadie (2010) [‡] , Salkin (2009) [‡]

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GS8	Repertoire of norms and strategies	Collection of actions and behaviors that actors regularly use, as shaped by the broader social and cultural setting	McGinnis and Ostrom (2014) [†] , Cettner et al. (2014a) [‡] , Cote and Wolfe (2014) [‡]
G-S8.1	Diversity	Degree of diversity in norms and strategies related to stormwater management decisions	Nowacek et al. (2003) [‡] , Hammitt (2010) [‡] , Madden (2010) [‡] , Winz et al. (2014) [‡]
G-S8.2	Risk tolerance	Degree to which actors are willing to take action in spite of uncertainties	(Singh, 2006) [‡] , Olorunkiya et al. (2012) [‡] , Cettner et al. (2014a) [‡]
GS9	Network structure	The connections among the rule-making organizations and the population subject to these rules	McGinnis and Ostrom (2014) ^a , Madden (2010) [‡] , Cettner et al. (2014) [‡] , Winz et al. (2014a) [‡]
G-S9.1	Horizontal	Connections that link actors with each other to act collectively for a common purpose	Shandas and Messer, (2008) [‡] , Madden (2010) [‡] , Keeley et al. (2013) [‡]
G-S9.2	Vertical	Connections that link actors with other organizations across levels	Hammitt (2010) [‡] , Dochow (2013) [‡] , Keeley et al. (2013) [‡] , Shuster et al. (2008) [‡]
G-S10 Actors (A)	Historical continuity	The length of time for which a particular form of governance has been in place Attributes of the individuals or groups that interact with resource units	McGinnis and Ostrom (2014) [†] McGinnis and Ostrom (2014) [†]
A1	Number of relevant actors	Number of actors affecting decision-making processes related to stormwater management in the watershed	Madden (2010) [‡] , Keeley et al. (2013) [‡] , Holloway et al. (2014) [‡]
A2	Socioeconomic attributes	Characteristics of actors related to social and economic dimensions affecting stormwater management plans	Hammitt (2010) [‡] , Montalto et al. (2013) [‡] , Keeley et al. (2013) [‡] , Travaline et al. (2015) [‡]
A3	History or past experiences	Past interactions that affect current actors' behaviors and stormwater management plans	Montalto et al. (2013) [‡] , Baptiste (2014) [‡] , Baptiste et al. (2015) [‡] , Travaline et al. (2015) [‡]
A3-.1	Experimentation	Variations in use patterns to increase knowledge of stormwater system dynamics (e.g., demonstration projects)	Madden (2010) [‡] , Shuster et al., (2013) [‡] , Marks (2014) [‡]
A3-.2	Environmental justice	Degree to which the development, implementation, and enforcement of stormwater management plans reflect a fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income	Perreault et al. (2012) [‡] , Flynn et al. (2014) [‡] , Wolch et al. (2014) [‡]

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A4	Location	Physical place where actors are in relation to components of the resource system	Thurston et al. (2010) [‡]
A5	Leadership/ entrepreneurship	Actors who have skills useful to organize collective action and are followed by their peers/ Non-exertion of power particularly of the public/	Hammitt (2010) [‡] , Winz et al. (2014) [‡]
A5-.1	Policy entrepreneur	Individuals who introduce and advocate for policy alternatives in many different settings, and invest time and energy to increase the chances for an idea to be placed on the decision agenda	Kingdon (1995) [†] , Godwin et al., (2008) [‡] , Madden (2010) [‡] , Flynn et al. (2014) [‡]
A5-.2	Policy community	Group composed of specialists in a given policy area developing policy alternatives	Kingdon (1995) [†] , Shandas and Messer, (2008) [‡] , Madden (2010) [‡] , Flynn et al. (2014) [‡]
A6	Norms (trust-reciprocity) and social capital	Degree by which one or several individuals can draw upon or rely on others for support or assistance in times of need	Hammitt (2010) [‡] , Cettner et al., (2014b) [‡] , Winz et al. (2014) [‡]
A6-.1	Trust	Measure of the extent to which members of a community feel confident that other members will not take maximum advantage of their vulnerabilities and/or live up to their agreements even if doing so may not be in their immediate interest.	McGinnis (2011) [†] , Nowacek et al. (2003) [‡] , Shandas and Messer, (2008) [‡] , Flynn et al. (2014) [‡] , Travaline et al. (2015) [‡]
A6-.2	Reciprocity	Norm of behavior that encourages members of a group to cooperate with others who have cooperated with them in previous encounters.	McGinnis (2011) [†] , Shandas and Messer, (2008) [‡] , Clean Water America Alliance (2011) [‡]
A6-.3	Social capital	Resources that an individual can draw upon in terms of relying on others to provide support or assistance in times of need, or a group's aggregate supply of such potential assistance, as generated by stable networks of important interactions among members of that community.	McGinnis (2011) [†] , Roy et al. (2008) [‡] , Dochow (2013) [‡] , Green et al. (2012) [‡]
A7	Knowledge of SES/mental models	Degree to which actors understand and make sense of the characteristics and/or dynamics of the SES	Basurto et al. (2013) [†] , Clean Water America Alliance (2011) [‡] ,
A7-.1	Types of knowledge	Types of knowledge actors use to understand SES	
A-7-.1.1	Traditional ecological knowledge	Degree to which actors make use of the cumulative body of knowledge, practices and beliefs evolving by adaptive processes and handed down through generations by cultural transmissions about the relationship of living beings (including humans) with one another and with their environment	Berkes (2012) [†] , Mbilinyi et al., (2005) [‡] , Flynn et al. (2014) [‡] , Winz et al. (2014) [‡]

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A-7-1.2	Local ecological knowledge	Degree to which actors make use of knowledge and beliefs held by a specific group of people related to their environment acquired over the lifetime of individual generations	Olsson and Folke (2001) [†] , McGarry (2007) [‡] , Winz et al. (2014) [‡] , Baptiste et al. (2015) [‡]
A-7-1.3	Technical expertise	Skills held by an actor related to specific technologies	Hammitt (2010) [‡] , Keeley et al. (2013) [‡] , Winz et al. (2014) [‡]
A7-.2	Mechanisms to share knowledge	Practices allow actors to learn characteristics of the resource at sufficiently rapid rates leading to behaviors affecting the state of the resource	Thurston et al. (2010) [‡] , Dolowitz et al. (2012) [‡] , Green et al. (2012) [‡]
A7-.3	Scale of mental models	Representation of the physical extent of actors' understanding regarding SES characteristics and dynamics	Madden (2010) [‡] , Hellier (2012) [‡] , (Cettner, 2012) [‡]
A8	Importance of resource (dependence)		Siglin (2012) [‡]
A9	Technology available	Attributes of the stormwater technologies available to actors	Clean Water America Alliance (2011) [‡]
A9-.1	Ownership	Degree to which stormwater management technologies are owned by various actors	Thurston et al. (2010) [‡] , Montalto et al. (2013) [‡] , Flynn et al. (2014) [‡]
A9-.2	Research support	Cumulative body of knowledge related to a specific technology	Roy et al. (2008) [‡] , Hammitt (2010) [‡] , Clean Water America Alliance (2011) [‡] , Dochow (2013) [‡]
A-9-2.1	Environmental performance and benefits	Extent of environmental outcomes associated with a technology	Stockwell (2009) [‡]
A9.2.-1.1	Stormwater management	Direct stormwater management control associated with a technology	Carter and Fowler (2008) [‡] , Clark and Pitt (2012) [‡] , Mayer et al. (2012) [‡] , Shuster and Rhea (2013) [‡]
A9.2.-1.2	Environmental outcomes	External environmental outcomes associated with a technology	Carter and Fowler (2008) [‡] , Madden (2010) [‡] , Wise et al. (2010) [‡] , Askarizadeh et al. (2015) [‡]
A-9-2.2	Social outcomes	Extent of social outcomes associated with a technology	Clean Water America Alliance (2011) [‡] , Kondo et al. (2015) [‡]

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A-9.-2.3	Complexity of design	Degree to which technology designs are easily replicable	Nowacek et al. (2003) [‡] , Roy et al. (2008) [‡] , Hammitt (2010) [‡] , Dochow (2013) [‡]
A-9.-3.4	Maintenance procedures	Known practices that maximize the continued functionality of a technology	Lord and Hunt (2008) [‡] , Clean Water America Alliance (2011) [‡] , Keeley et al. (2013) [‡]
A-9.-2.5	Reliability	Extent to which a technology produces the same outcomes on repeated trials	Nowacek et al. (2003) [‡] , Olorunkiya et al. (2012) [‡]
A9-.3	Associated costs	Expenses related to a technology	Perez-Pedini et al. (2005) [‡] , Roy et al. (2008) [‡] , Jaffe (2011) [‡] , Dochow (2013) [‡]
A-9.-3.1	Capital	Fixed, one-time expenses related to the implementation of a technology	Winz et al. (2014) [‡] , Thurston et al. (2010) [‡] , Cote and Wolfe (2014) [‡]
A-9.-3.2	Operation and maintenance	Ongoing expenses related to the operation and maintenance of a technology	Clean Water America Alliance (2011) [‡] , Keeley et al. (2013) [‡] , Winz et al. (2014) [‡]
A9-.4	Perceptions/ attitudes	Subjective assessments on various technology attributes	Siglin (2012) [‡] , Keeley et al. (2013) [‡] , Marks (2014) [‡] , Carlet (2015) [‡]
Activities and Processes (I)			
I1	Harvesting	Gathering of resource units	
I2	Information sharing	Exchanges of knowledge between actors and/or groups	Roy et al. (2008) [‡] , Madden (2010) [‡] , Dolowitz et al. (2012) [‡]
I3	Deliberation processes	Activities related to the of weighing options	Madden (2010) [‡]
I4	Conflicts	Form of disagreement or discord that arise when the beliefs or actions of one or more members of a group are either resisted by or unacceptable to one or more members of another group	Flynn et al. (2014) [‡]
I5	Investment activities	Contributions of financial and other resources by the managers or producers of a public good/service	McGinnis (2011) [‡] , Hammitt (2010) [‡] , Madden (2010) [‡]
I6	Lobbying activities	Actions that attempt to influence decisions made by rule-making individuals and/or organizations	Madden (2010) [‡]
I7	Self-organizing activities	Interactions among actors that increase some form of overall order or coordination	Roy et al. (2008) [‡] , Winz et al. (2014) [‡]

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I8	Networking activities	Meetings which build social structure between actors, connecting them through various social familiarities	Roy et al. (2008) [‡] , Hammitt (2010) [‡] , Madden (2010) [‡]
I9	Monitoring activities	Accumulation of new knowledge related to system attributes	Stockwell (2009) [‡] , Flynn et al. (2014) [‡] , Askarizadeh et al. (2015) [‡]
I10	Evaluative activities	Determination of which aspects of the observed outcomes are deemed satisfactory and which aspects are in need of improvement	McGinnis (2011) [†] , Madden (2010) [‡] , Winz et al. (2014) [‡]
Outcome Criteria (O)		Evaluative criteria used to determine which aspects of observed outcomes are deemed satisfactory and which aspects are in need of improvement.	McGinnis (2011) [†] , Holloway et al. (2014) [‡]
O1	Social performance measures	Indicators that describe various social conditions	Brown and Farrelly (2008) [‡] , Madden (2010) [‡] , Winz et al. (2014) [‡]
O2	Ecological performance measures	Indicators that describe various ecological conditions	Burns et al. (2012) [‡] , Mayer et al. (2012) [‡] (Roy et al., 2014) [‡]
O3	Externalities to other SESs	Indicators that describe impacts on other SESs	Tzoulas et al. (2007) [‡] , Foster et al. (2011) [‡] , Mayer et al. (2012) [‡]
Related ecosystems (ECO)		The broader ecological context within which the focal resource system is located, including the determinants of many potential exogenous influences	McGinnis and Ostrom (2014) [†]
E-C-O1	Climate patterns	Recurring characteristics of the statistical distribution of weather over an extended period of time	Clean Water America Alliance (2011) [‡]
E-C-O2	Pollution patterns	Recurring characteristics of contaminants that cause adverse effects	Lassiter (2007) [‡] , Hammitt (2010) [‡]
E-C-O3	Flows into and out of focal SES	Movement patterns of various SES attributes	Nowacek et al. (2003) [‡] , Madden (2010) [‡] , Winz et al. (2014) [‡]

[†]Reference for attribute definition

[‡] Reference that provides illustration of example of attribute's relationship to green infrastructure adoption in urban stormwater SESs

LITERATURE CITED

Askarizadeh, A., M.A. Rippy, T.D. Fletcher, D.L. Feldman, J. Peng, P. Bowler, A.S. Mehring, B.K. Winfrey, J.A. Vrugt, A. AghaKouchak, S.C. Jiang, B.F. Sanders, L.A. Levin, S. Taylor, and S.B. Grant. 2015. From Rain Tanks to Catchments: Use of Low-Impact Development to Address Hydrologic Symptoms of the Urban Stream Syndrome. *Environmental Science and Technology*. 49(19), 11264-11280. doi:10.1021/acs.est.5b01635

Baptiste, A.K. 2014. "Experience is a great teacher": citizens' reception of a proposal for the implementation of green infrastructure as stormwater management technology. *Community Development* 45(4), 337-352. doi:10.1080/15575330.2014.934255

Baptiste, A.K., C. Foley, and R. Smardon. 2015. Understanding urban neighborhood differences in willingness to implement green infrastructure measures: a case study of Syracuse, NY. *Landscape and Urban Planning* 136, 1-12. doi:10.1016/j.

landurbplan.2014.11.012

Basurto, X., S. Gelcich, and E. Ostrom. 2013. The social-ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Global Environmental Change* 23(6): 1366-1380. doi:10.1016/j.gloenvcha.2013.08.001

Berkes, F. 2012. *Sacred Ecology*, 3rd ed. Routledge, New York, New York, U.S.A.

Brown, R., and M. Farrelly. 2008. Sustainable urban stormwater management in Australia: professional perceptions on institutional drivers and barriers, in: *Proceedings of the 11th International Conference on Urban Drainage*, Edinburgh, Scotland. Citeseer.

Burns, M.J., T.D. Fletcher, C.J. Walsh, A.R. Ladson, and B.E. Hatt. 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. *Landscape and Urban Planning* 105(3), 230-240.

Carlet, F. 2015. Understanding attitudes toward adoption of green infrastructure: A case study of US municipal officials. *Environmental Science & Policy*. 51, 65-76. doi:10.1016/j.envsci.2015.03.007

Carter, T., and L. Fowler. 2008. Establishing Green Roof Infrastructure Through Environmental Policy Instruments. *Environmental Management* 42(1), 151-164. doi:10.1007/s00267-008-9095-5

Cettner, A. 2012. *Overcoming inertia to sustainable stormwater management practice* (PhD Thesis). Lulea University of Technology: Lulea, Sweden.

Cettner, A., R. Ashley, A. Hedström, and M. Viklander, M. 2014a. Assessing receptivity for change in urban stormwater management and contexts for action. *Journal of Environmental Management* 146, 29-41. doi:10.1016/j.jenvman.2014.07.024

Cettner, A., R. Ashley, A. Hedström, and M. Viklander, M. 2014b. Sustainable development and urban stormwater practice. *Urban Water Journal* 11(3), 185-197. doi:10.1080/1573062X.2013.768683

Clark, S.E., R. Pitt. 2012. Targeting treatment technologies to address specific stormwater pollutants and numeric discharge limits. *Water Research*. 46(20), 6715-6730. doi:10.1016/j.watres.2012.07.009

Clean Water America Alliance, 2011. *Barriers and Gateways to Green Infrastructure*. Washington D.C., U.S.A.

Cote, S.A., and S. Wolfe. 2014. Assessing the Social and Economic Barriers to Permeable Surface Utilization for Residential Driveways in Kitchener, Canada. *Environmental Practice* 16, 6-18. doi:10.1017/S1466046613000641

Debo, T.N., and A. Reese. 2003. *Municipal stormwater management*, Second Edition. ed. CRC Press, Boca Raton, Florida, U.S.A.

Dietz, M.E., and J.C. Clausen, J.C. Stormwater runoff and export changes with development in a traditional and low impact subdivision. *Journal of Environmental Management* 87(4), 560-566.

Dochow, D., 2013. *Transforming Tradition: A Case Study of Stormwater Management in Clark County, Washington to Assess Barriers to Low Impact Development Strategies* (MA Thesis). Evergreen State College. Olympia, Washington, U.S.A. [online] http://archives.evergreen.edu/masterstheses/Accession86-10MES/Dochow_D2013.pdf

Dolowitz, D., M. Keeley, and D. Medearis. 2012. Stormwater management: can we learn from others? *Policy Studies*. 33(6), 501-521. doi:10.1080/01442872.2012.722289

Dunn, A.D. 2010. Siting green infrastructure: legal and policy solutions to alleviate urban poverty and promote healthy communities. *Boston College Environmental Affairs Law Review*. 37, 41.

Epstein, G., J.M. Vogt, S.K. Mincey, M. Cox, and B. Fischer. 2013. Missing ecology: integrating ecological perspectives with the social-ecological system framework. *International Journal of the Commons* 7(2), 432-453.

Fletcher, T.D., C.J. Walsh, D. Bos, V. Nemes, S.R. Rakesh, T. Prosser, B. Hatt, and R. Birch. 2011. Restoration of stormwater retention capacity at the allotment-scale through a novel economic instrument. *Water Science & Technology*. 64(2).

Flynn, C.D., C.I. Davidson, and J. Mahoney. 2014. Transformational Changes Associated with Sustainable Stormwater Management Practices in Onondaga County, New York. In *ICSI 2014: Creating Infrastructure for a Sustainable World*, eds. J. Crittenden, C. Hendrickson, and B. Wallace, November 2014, pp. 89-100. doi: 10.1061/9780784478745.009

- Foster, J., A. Lowe, and S. Winkelman. 2011. *The value of green infrastructure for urban climate adaptation*. Center for Clean Air Policy, February. Washington, D.C., U.S.A.
- Godwin, D., B.L. Parry, F.A. Burris, S.S. Chan, and A. Punton. 2008. *Barriers and opportunities for low impact development: case studies from three Oregon Communities*. Oregon Sea Grant, Oregon State University Corvallis, Oregon, U.S.A.
- Green, O.O., W.D. Shuster, L.K. Rhea, A.S. Garmestani, and H.W. Thurston. 2012. Identification and induction of human, social, and cultural capitals through an experimental approach to stormwater management. *Sustainability*. 4(8), 1669-1682.
- Hammitt, S.A. 2010. *Toward sustainable stormwater management: overcoming barriers to green infrastructure* (MS Thesis). Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S.A. [online] URL: http://www.mit.edu/afs.new/athena/dept/cron/project/urban-sustainability/Stormwater_Sarah%20Madden/Shammitt_thesis_final.pdf
- Hellier, J. 2012. *Ecologists and Organizers: Participatory Research for Shared Understanding in the Green Seattle Partnership* (MS Thesis). University of Washington. Seattle, Washington, U.S.A. [online] <https://dlib.lib.washington.edu/researchworks/handle/1773/20555>
- Holloway, C.F., C.H. Strickland Jr, M.B. Gerrard, and D.M. Firger. 2014. Solving the CSO Conundrum: Green Infrastructure and the Unfulfilled Promise of Federal-Municipal Cooperation. *Harvard Environmental Law Review*. 38, 335.
- Jaffe, M.S., M. Zellner, E. Minor, M. Gonzalez-Meler, L. Cotner, D. Massey, H. Ahmed, M. Elberts, H. Sprague, S. Wise, and B. Miller. 2010. Using green infrastructure to manage urban stormwater quality: a review of selected practices and state programs. *Illinois Environmental Protection Agency*. Springfield, IL, USA.
- Jaffe, M. 2011. Environmental Reviews & Case Studies: Reflections on Green Infrastructure Economics. *Environmental Practice* 12 (04), 357-365. doi:10.1017/S1466046610000475
- Jensen, M.A. 2008. *Feasibility of rainwater harvesting for urban water management in Salt Lake City* (MS Thesis). The University of Utah. Salt Lake City, Utah, U.S.A. [online] <http://content.lib.utah.edu/cdm/ref/collection/etd2/id/1406>
- Keeley, M., A. Koburger, D.P. Dolowitz, D. Medearis, D. Nickel, and W. Shuster. 2013. Perspectives on the Use of Green Infrastructure for Stormwater Management in Cleveland and Milwaukee. *Environmental Management* 51(6), 1093-1108. doi:10.1007/s00267-013-0032-x
- Kertesz, R., O.O. Green, and W.D. Shuster. 2014. Modeling the hydrologic and economic efficacy of stormwater utility credit programs for US single family residences. *Water Science & Technology* 70(11).
- Kingdon, J.W. 1995. *Agendas, Alternatives and public policies*. Harper Collins. New York, New York, USA.
- Kondo, M.C., S.C. Low, J. Henning, and C.C. Branas. 2015. The Impact of Green Stormwater Infrastructure Installation on Surrounding Health and Safety. *American Journal of Public Health*. 105(3), e114-e121. doi:10.2105/AJPH.2014.302314
- Kulkarni, M. 2012. *Implementation of green infrastructure as stormwater management in Portland, Oregon* (MS Report). Kansas State University. Manhattan, Kansas, U.S.A. [online] <https://krex.k-state.edu/dspace/handle/2097/13780>
- LaBadie, K. 2010. *Identifying barriers to low impact development and green infrastructure in the Albuquerque Area* (MS Thesis). The University of New Mexico. Albuquerque, New Mexico, U.S.A. [online] www.wrri.nmsu.edu/research/rfp/studentgrants08/reports/LaBadie.pdf
- Lassiter, R. 2007. *An Assessment of Impediments to Low-Impact Development in the Virginia Portion of the Chesapeake Bay Watershed* (MS Thesis). Virginia Commonwealth University. Richmond, Virginia, U.S.A. [online] <http://scholarscompass.vcu.edu/etd/892/?mode=full>
- Lord, W.G., and W.F. Hunt. 2008. Stormwater BMP Maintenance and Certification Program in North Carolina, USA. In *Low Impact Development for Urban Ecosystem and Habitat Protection*. eds. N. She; and M. Char. American Society of Civil Engineers. pp. 1-6. doi: 10.1061/41009(333)64
- Madden, S. A. 2010. *Choosing green over gray: Philadelphia's innovative stormwater infrastructure plan*. Massachusetts Institute of Technology. Cambridge, Massachusetts, U.S.A. [online] URL: http://www.mit.edu/afs.new/athena/dept/cron/project/urban-sustainability/Stormwater_Sarah%20Madden/sarahmadden_thesis_MIT.pdf

- Marks, A. 2014. Stormwater management in Boston: to what extent are demonstration projects likely to enable citywide use of green infrastructure? Massachusetts Institute of Technology.
- Mayer, A.L., W.D. Shuster, J.J. Beaulieu, M.E. Hopton, L.K. Rhea, A.H. Roy, and H.W. Thurston. 2012. Environmental reviews and case studies: Building green infrastructure via citizen participation: A six-year study in the Shepherd Creek (Ohio). *Environmental Practice*. 14(01), 57-67.
- Mbilinyi, B.P., S.D. Tumbo, H.F. Mahoo, E.M. Senkondo, and N. Hatibu. 2005. Indigenous knowledge as decision support tool in rainwater harvesting. *Physics and Chemistry of the Earth, Parts A/B/C*. 30(11-16), 792-798. doi:10.1016/j.pce.2005.08.022
- McGarry, S. 2007. *Local Ecological Knowledge of Flooding in the Madison Valley Neighborhood of Seattle, Washington* (MA Thesis). Evergreen State College. Olympia, Washington, U.S.A. [online] http://archives.evergreen.edu/masterstheses/Accession86-10MES/McGarry_S%20MESThesis%202007.pdf
- McGinnis, M.D. 2011. An introduction to IAD and the language of the Ostrom workshop: a simple guide to a complex framework. *Policy Studies Journal* 39(1), 169-183.
- McGinnis, M. D., E. and Ostrom. 2014. Social-ecological framework: initial changes and continuing challenges. *Ecology and Society* 19(2): 30. <http://dx.doi.org/10.5751/ES-06387-190230>
- Montalto, F.A., T.A. Bartrand, A.M. Waldman, K.A. Travaline, C.H. Loomis, C. McAfee, J.M. Geldi, G.J. Riggall, and L.M. Boles. 2013. Decentralised green infrastructure: the importance of stakeholder behaviour in determining spatial and temporal outcomes. *Structure and Infrastructure Engineering* 9(12), 1187-1205.
- Nowacek, D., E. Nelson, and J. Petchenik. 2003. *Social and Institutional Barriers to Stormwater Infiltration*. Wisconsin Department of Natural Resources-Bureau of Integrated Science Services. Madison, Wisconsin, U.S.A. [online] www.kitsaplid.org/resources/Barriers_to_SW_Infiltration.pdf
- Olorunkiya, J., E. Fassman, and S. Wilkinson. 2012. Risk: A fundamental barrier to the implementation of low impact design infrastructure for urban stormwater control. *Journal of Sustainable Development*. 5(9), 27.
- Olsson, P., and C. Folke. 2001. Local ecological knowledge and institutional dynamics for ecosystem management: A study of Lake Racken watershed, Sweden. *Ecosystems*. 4(2), 85-104.
- Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences* 104(39), 15181-15187. doi:10.1073/pnas.0702288104
- Ostrom, E., R. Gardner, and J. Walker. 1994. *Rules, Games, and Common-pool Resources*. University of Michigan Press. Ann Arbor, Michigan, U.S.A.
- Parikh, P., M.A. Taylor, T. Hoagland, H. Thurston, and W. Shuster. 2005. Application of market mechanisms and incentives to reduce stormwater runoff: An integrated hydrologic, economic and legal approach. *Environmental Science & Policy*. 8(2), 133-144.
- Perez-Pedini, C., J.F. Limbrunner, and R.M. Vogel. 2005. Optimal location of infiltration-based best management practices for storm water management. *Journal of Water Resources Planning and Management* 131(6), 441-448.
- Perreault, T., S. Wraight, and M. Perreault. 2012. Environmental injustice in the Onondaga lake waterscape, New York State, USA. *Water Alternatives* 5(2), 485-506.
- Rhea, L., W. Shuster, J. Shaffer, and R. Losco. 2014. Data proxies for assessment of urban soil suitability to support green infrastructure. *Journal of Soil and Water Conservation*. 69(3), 254-265.
- Roy, A.H., L.K. Rhea, A.L. Mayer, W.D. Shuster, J.J. Beaulieu, M.E. Hopton, M.A. Morrison, and A.S. Amand. 2014. How Much Is Enough? Minimal Responses of Water Quality and Stream Biota to Partial Retrofit Stormwater Management in a Suburban Neighborhood. *PLoS One* 9(1), e85011. doi:<http://dx.doi.org.libezproxy2.syr.edu/10.1371/journal.pone.0085011>
- Roy, A.H., and W.D. Shuster. 2009. Assessing impervious surface connectivity and applications for watershed management. *Journal of the American Water Resources Association*. 45(1), 198-209.
- Roy, A.H., S.J. Wenger, T.D. Fletcher, C.J. Walsh, A.R. Ladson, W.D. Shuster, H.W. Thurston, and R.R. Brown. 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States.

Environmental management. 42(2), 344-359.

Salkin, P.E. 2009. Sustainability and Land Use Planning: Greening State and Local Land Use Plans and Regulations to Address Climate Change Challenges and Preserve Resources for Future Generations. *William and Mary Environmental Law and Policy Review*. 34, 121.

Shandas, V., and W. B. Messer. 2008. Fostering Green Communities Through Civic Engagement: Community-Based Environmental Stewardship in the Portland Area. *Journal of the American Planning Association*. 74(4), 408-418. doi:10.1080/01944360802291265

Shuster, W., and L. Rhea. 2013. Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). *Journal of hydrology*. 485, 177-187.

Shuster, W.D., S. Dadio, P. Drohan, R. Losco, and J. Shaffer. 2014. Residential demolition and its impact on vacant lot hydrology: Implications for the management of stormwater and sewer system overflows. *Landscape and Urban Planning*. 125, 48-56.

Shuster, W.D., A.S. Garmestani, O.O.Green, L.K. Rhea, A.H. Roy, and H.W. Thurston. 2013. Catchment-scale stormwater management via economic incentives-an overview and lessons-learned, in: *Proceedings of the 8th International Conference of NOVATECH*. GRAIE, Lyon, France.

Shuster, W.D., M.A. Morrison, and R. Webb. 2008. Front-loading urban stormwater management for success - A perspective incorporating current studies on the implementation of retrofit low-impact development. *Cities and the Environment*.1(2), 8.

Siglin, D.D. 2012. *Municipal Use of Green Stormwater Infrastructure in The Delaware River Basin: Barriers, Drivers, And Opportunities for Implementation* (MS Thesis). The Pennsylvania State University. State College, Pennsylvania, U.S.A. [online] <https://etda.libraries.psu.edu/paper/15290/12231>

Singh, C. 2006. *The process of and barriers to environmentally-oriented real estate development: examining the role of organizational structure, project delivery methods and contracts in low impact development* (MS Thesis). Massachusetts Institute of Technology. Cambridge, Massachusetts, U.S.A. [online] <http://dspace.mit.edu/handle/1721.1/37465>

Stockwell, A. 2009. *Analysis of Barriers to Low Impact Development in the North Coast Redwood Region, California* (MS Thesis). Humboldt State University. Arcata, California, U.S.A. [online] <http://humboldt-dspace.calstate.edu/handle/2148/595>

Thurston, H.W., H.C. Goddard, D. Szlag, and B. Lemberg. 2003. Controlling storm-water runoff with tradable allowances for impervious surfaces. *Journal of Water Resources Planning and Management* 129(5), 409-418.

Thurston, H.W., M.A. Taylor, W.D. Shuster, A.H. Roy, and M.A. Morrison. 2010. Using a reverse auction to promote household level stormwater control. *Environmental Science & Policy*. 13(5), 405-414.

Travaline, K., F. Montalto, and C. Hunold. 2015. Deliberative Policy Analysis and Policy-making in Urban Stormwater Management. *Journal of Environmental Policy & Planning*. 17(5), 691-708. doi:10.1080/1523908X.2015.1026593

Tzoulas, K., K. Korpela, S. Venn, V. Yli-Pelkonen, A. Kaźmierczak, J. Niemela, and P. James. 2007. Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. *Landscape and Urban Planning*. 81(3), 167-178.

Winz, I., S. Trowsdale, and G. Brierley. 2014. Understanding barrier interactions to support the implementation of sustainable urban water management. *Urban Water Journal* 11(6), 497-505.

Wise, S., J. Braden, D. Ghalayini, J. Grant, C. Kloss, E. MacMullan, S. Morse, F. Montalto, D. Nees, D. Nowak, S. Peck, S. Shaikh, and C. Yu. 2010. Integrating Valuation Methods to Recognize Green Infrastructure's Multiple Benefits, in: *Low Impact Development 2010: Redefining Water in the City*. Eds. S. Struck, and K. Lichten. American Society of Civil Engineers, pp. 1123-1143. doi: 10.1061/41099(367)98

Wolch, J.R., J. Byrne, and J.P. Newell. 2014. Urban green space, public health, and environmental justice: The challenge of making cities "just green enough." *Landscape and Urban Planning*. 125, 234-244. doi:10.1016/j.landurbplan.2014.01.017
