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# Transitioning to Sustainable Civil Infrastructure Systems: Green Stormwater Management and Engineering Design Thinking

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# Abstract

Green infrastructure has been endorsed by many practitioners and organizations as a more sustainable approach to stormwater management. Decisions on how to best design municipal green infrastructure systems can be complicated by factors such as uncertainties about the performance and public acceptance of particular technologies. Thus, deciding how to design sustainable stormwater management systems requires engineers not only to reflect upon the fundamental principles used to conceptualize their designs, but also to consider how a broad array of social, economic, and environmental factors both influence and are influenced by their work.

This thesis examines factors that influence the design and adoption of sustainable civil infrastructure systems in two research areas: (1) municipal stormwater management decisions in the United States, and (2) student understanding of engineering design principles. The objective of this thesis is to identify elements of engineering design and related decision-making processes that can provide engineers, stormwater management stakeholders, and engineering educators with lessons and tools that can advance the sustainable development of stormwater management systems.

One challenge to understanding how particular factors may lead to sustainable outcomes is devising a tractable way to organize and document them. Using observations from national meetings and an extensive literature review, I develop a social-ecological framework for identifying factors that condition the adoption of green infrastructure technologies by stormwater management authorities. Findings from this work demonstrate a need to more fully develop robust descriptions of technological attributes within a social-ecological framework for urban stormwater systems, particularly for technology decision-making activities such as green infrastructure adoption.

Understanding past outcomes of engineering planning within a particular context can provide useful insight for future decision-making. I conduct a case study on the evolution of stormwater management planning in Onondaga County, New York between 1998 and 2009, in which plans for certain unpopular gray infrastructure technologies were eventually replaced in part by a large-scale green infrastructure program. I find that the adoption of this program was driven by an alignment of several sociopolitical factors, including the presence of a policy entrepreneurship coalition in support of alternative stormwater management plans, the election of a key political official who acknowledged the needs of local stakeholders, and a shift in mindset of local and national officials as to what technologies are effective for stormwater management.

A growing number of U.S. cities are adopting green infrastructure programs for stormwater management, particularly for combined sewer overflow mitigation. Viewing green infrastructure program adoption in combined sewer communities as a policy innovation, I develop an empirical model to differentiate factors associated with a sewer management authority's binary decision to adopt or not adopt a large-scale green infrastructure program, and factors associated with decisions related to the extent of planned program implementation. This study finds that the binary decision to adopt a municipal green infrastructure program for combined sewer overflow management is largely driven by municipal population size and precipitation characteristics, while the extent of program implementation is also driven by socioeconomic characteristics of municipal residents and the amount of total capital needs required to achieve combined sewer overflow compliance.

Engineers must be able to mathematically model the complexities of fundamental physical processes within real systems, such as green infrastructure systems for stormwater management. Many engineering processes are built upon fundamental concepts of mass and energy balances, in which mathematical models are used to analyze rates of change and accumulated quantities across system boundaries of interest. The Rate and Accumulation Concept Inventory (RACI) is an assessment tool that I developed to measure students' mathematical and physical understandings of such concepts. I use data from an administration of the RACI (N=305) to assess evidence of the tool's validity and reliability through structural equation modeling and multidimensional item response theory. Validity and reliability evidence indicates that the RACI can appropriately be used to measure students' overall understanding of rate and accumulation processes.

Case-based teaching methods have been suggested as a best practice for introducing students to ethical decision-making scenarios. By sensitizing future engineers to the concerns of stakeholders who are impacted by engineering decisions, educators can better prepare them to create designs that address social outcome criteria such as welfare and justice. Using case study findings related to stakeholder concerns and engineering decisions for stormwater management planning in Onondaga County, I develop a case-based teaching module on engineering decision-making for use in undergraduate civil and environmental engineering courses. Assessments from three years of module implementation demonstrate that the module can be used to meet multiple learning objectives and enhance student understanding of stakeholder engagement principles.

# TRANSITIONING TO SUSTAINABLE CIVIL INFRASTRUCTURE SYSTEMS:

# GREEN STORMWATER MANAGEMENT AND ENGINEERING DESIGN THINKING

by

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DISSERTATION

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# Chapter 1 Introduction

## 1.1 Motivation

Anthropogenic environmental changes have eroded the resilience of major components of ecosystem functioning that provide the appropriate living environments and ecological services that humanity depends on to exist (Rockström et al., 2009). Sustainable development is widely recognized as an essential strategy to decrease the negative impacts of anthropogenic activities, despite multiple interpretations of its underlying concepts (Glavič and Lukman, 2007; Redclift, 2005; WCED, 1987). Attainment of large-scale sustainable development goals requires collaborative efforts across governments, corporations, nonprofit organizations, academia, and individuals.

Engineers can play a pivotal role in the design and implementation of sustainable development strategies. Several professional engineering organizations have responded to concerns of sustainable development by adopting principles of sustainable engineering design and amending their codes of practice. For instance, the American Society of Civil Engineers amended its first Code of Ethics Canon in 1996 to include sustainable development principles (ASCE, 2008). While the need to consider sustainability as an inherent part of engineering practice has been widely accepted, embedding it in daily practice remains to be fully realized (Jones et al., 2017).

Many researchers argue that there is a need to integrate the physical and social science disciplines with engineering to address the ecological, economic, and social processes of sustainable development (Clark and Dickson, 2003; Kates et al., 2001; Mihelcic et al., 2003). The importance of interdisciplinary efforts in building sustainable solutions to critical environmental problems is becoming more apparent to many policy makers, scientists, and engineers who seek to encourage research and education at the interfaces of different disciplines (Hollander et al., 2016). Interdisciplinary and transdisciplinary research that balances disciplinary perspectives and actively involves stakeholders and decision-makers can provide research that is both more useful and readily accepted (Reid et al., 2010).

There are considerable challenges to integrating sustainable engineering into undergraduate education, particularly in addressing the normative social dimensions of sustainable development (Allenby et al., 2009). It is unrealistic to expect students with little "real-world" experience to understand the complexities of sustainable engineering design through traditional instructional methods. Instead, introducing pedagogical elements such as historical context, decision-making problems, and ethical problems into the classroom can help students to develop a sustainable design mindset. At the same time, conceptual knowledge of fundamental mathematic and scientific principles is central to the practice of engineering (Sheppard et al., 2007; Streveler et al., 2008). Thus, engineering students must develop deep conceptual understandings of both the engineering processes that underlie complex environmental systems as well as the broad array of social and economic factors that influence the design of sustainable engineered systems.

## 1.2 Urban Water Infrastructure Systems

Cities across the U.S. are facing mounting water crises that threaten social and environmental sustainability due to population growth, deteriorating infrastructure, and climate change. These issues stem in part from unforeseen consequences of engineering system designs that fail to incorporate the complexity of social and ecological factors that are affected by these systems. For instance, the rationale that 19th and early 20th century engineers used to build thousands of miles of combined sewer systems throughout the U.S. has left a legacy of water pollution problems that policy-makers continue to deal with today (Tarr, 1979). As an immediate replacement of centralized urban water systems is an economically unrealistic option, transitions toward sustainable water systems through redevelopment projects will be needed to provide adequate water services for future generations (Daigger, 2009; Sedlak, 2014).

Traditionally, water infrastructure decisions have been framed from a function, safety, and cost perspectives, without important stakeholders effectively engaged in developing integrated, sustainable solutions (Guest et al., 2009). While many technological approaches exist that can transition water infrastructure systems to more sustainable and resilient states, their implementation is limited by institutional impediments and uncertainties about the design, performance, and life cycle costs of new technologies. Thus, there is a need for more robust decision-making frameworks for water infrastructure systems that integrate evaluation methods based on sustainable development principles and engagement with a wide range of stakeholders in defining and implementing solutions

## 1.3 Thesis Overview

In summary, challenges to sustainable stormwater management include a lack of appropriate design and planning methodologies that incorporate interdisciplinary research to identify and implement the most sustainable solution in a particular context. Similarly, challenges to educating the next generation of engineers include a lack of appropriate educational tools that adequately prepare students to take on such approaches to sustainable engineering design. The objective of this thesis is to identify elements of such a decision-making methodology that can provide engineers, stormwater management stakeholders, and engineering educators with lessons and tools that can advance the sustainable development of stormwater management systems. This work brings together an assessment of sustainable stormwater management planning in the United States with investigations of student understanding of engineering design principles. The intent of this research is to explore two different but related problems: (1) a need to understand key factors affecting sustainable stormwater technology adoption and implementation in municipalities, and (2) a need for engineering students to apply fundamental scientific and mathematical principles while incorporating complex social constraints within engineering design problems. This thesis includes five chapters that aim to address these challenges of sustainable engineering design.

Interdisciplinary research is facilitated when common vocabulary is shared by scholars working on a particular system of interest. A framework is a type of ontology that can aid in the organization and accumulation of knowledge from empirical studies through a shared understanding the concepts and terms used in interdisciplinary research endeavors. In Chapter 2, I propose a framework for identifying factors that condition the adoption of green infrastructure technologies by stormwater management authorities. The application of this framework can be useful in the analysis of social-ecological outcomes at multiple scales. Chapter 3 presents a case study that utilizes the revised framework to describe and evaluate changes in stormwater management planning in Onondaga County, NY between 1998 and 2009. In Chapter 4, I use select factors from the framework to build an empirical model to analyze combined sewer management authorities' decisions related to green infrastructure program adoption.

Many engineering processes are built upon the basic principles of mass and energy balances, which invoke the use of mathematical models derived from the fundamental theorem of calculus to analyze rates of change and accumulation across system boundaries of interest. Chapter 5 provides evidence of the validity and reliability of an assessment tool designed to measure students' understanding of rate and accumulation concepts. Investigating various social elements of engineering practice in the classroom can improve students' recognition of ethical problems in real-world settings and provide an understanding of sustainable decision-making. Chapter 6 describes the development and use of a case-based active-learning module to enhance student understanding of stakeholder engagement principles.

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# Chapter 2 Adapting the social-ecological system framework for urban stormwater management: The case of green infrastructure adoption[1]

## 2.1 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.

## 2.2 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

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[1] This paper is published in the *Ecology and Society*. It is cited in the rest of the dissertation as Flynn and Davidson (2016).

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 (U.S. EPA 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, large-scale use of GI in stormwater management planning 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 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.

## 2.3 Methods

The identification of attributes associated with GI adoption in municipal urban stormwater programs included several phases of data collection and analysis (Fig. 2.1). 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.

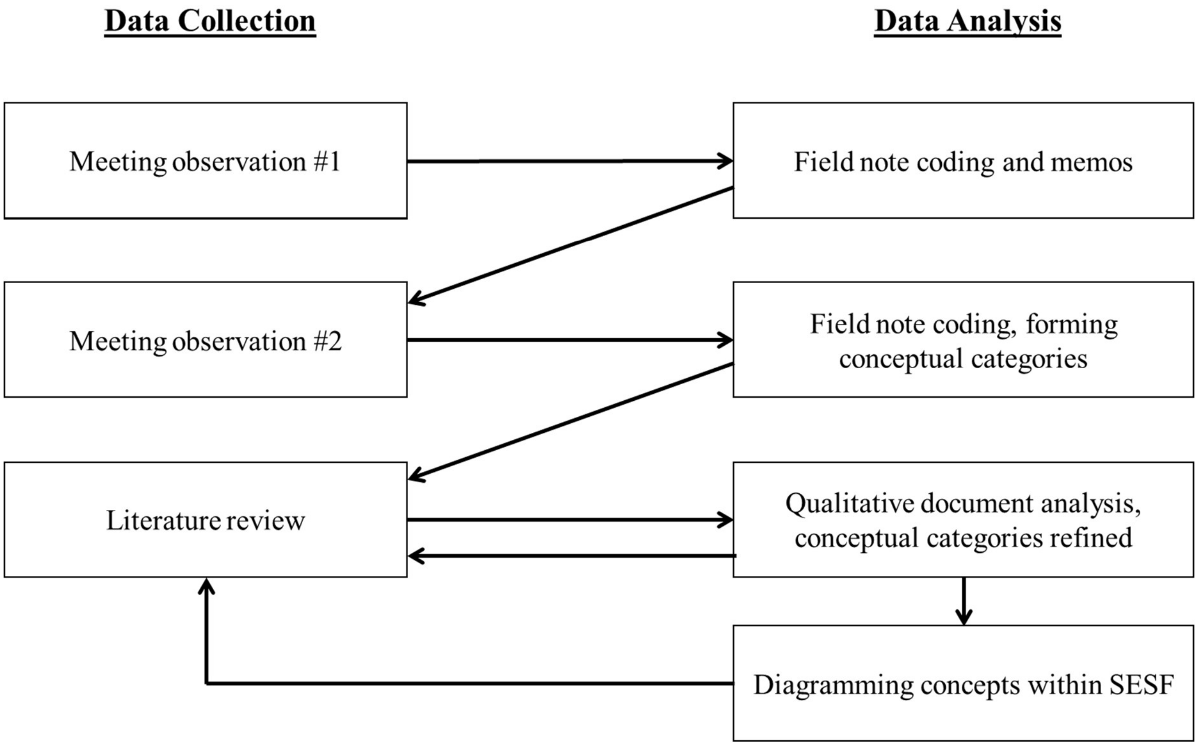

**Figure 2.1 Sequence of data collection and analysis**

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 are "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.

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 2.1. Working definitions were developed for each attribute and are included in Appendix A2, 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.

## 2.4 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. 2.2. 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).

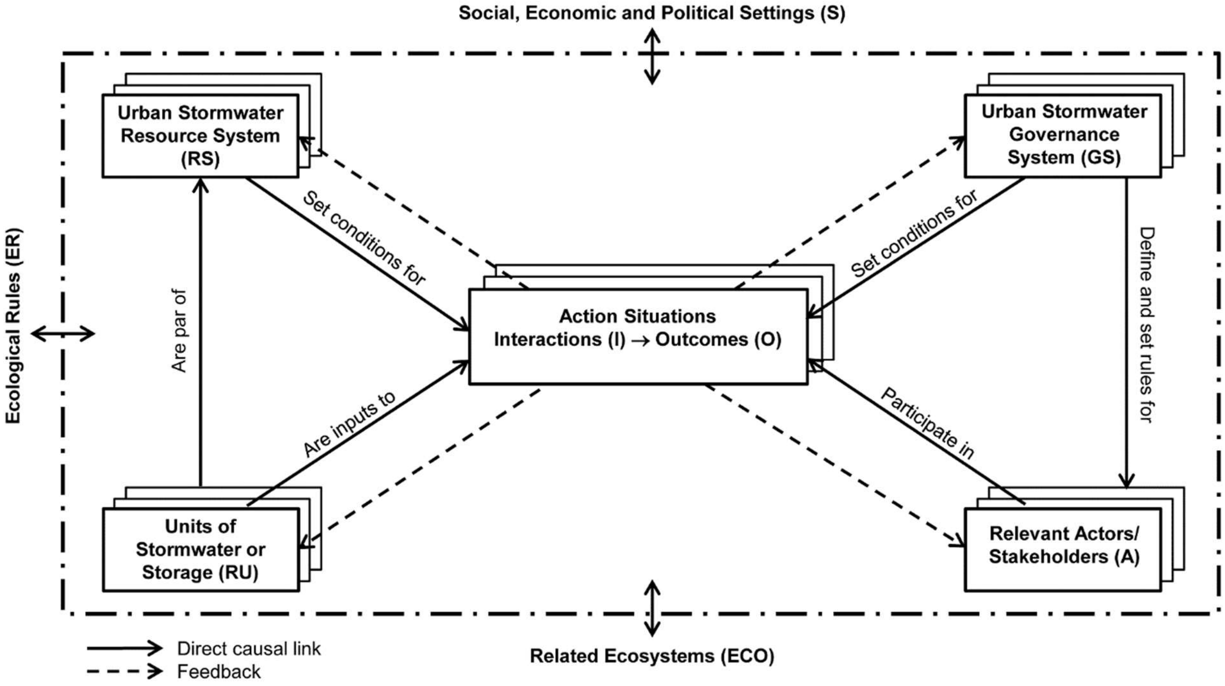

**Figure 2.2 First tiers of the urban stormwater SESF, adapted from Ostrom (2009) and Epstein et. al (2013)**

Table 2.1 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 A2. 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

**Table 2.1 Modified second through fifth tier attributes of the urban stormwater SES framework. Factors modified from McGinnis and Ostrom (2014), Epstein et. al (2013), and Vogt et. al (2015) that are specific for GI adoption in urban stormwater SESs are noted with italic**

**Social, Economic, and Political Settings (S)**

- S1 – Economic development
- S2 – Demographic trends
- S3 – Political stability
- S4 – Government policies
- S5 – Market incentives
- S6 – Media organization
- S7 – Technology

**Related Ecosystems (ECO)**

- ECO1 – Climate patterns
- ECO2 – Pollution patterns
- ECO3 – Flows into and out of focal SES

**Ecological Rules (ER)**

- ER1 – Physical Rules
- ER2 – Chemical Rules
- ER3 – Biological Rules
- ER3 – Biological Rules

**Action Situations: Interactions (I) → Outcomes (O)**

**Interactions (I)**

- I1 – Harvesting
- I2 – Information sharing
- I3 – Deliberation processes
- I4 – Conflicts
- I5 – Investment activities
- I6 – Lobbying activities
- I7 – Self-organizing activities
- I8 – Networking activities
- I9 – Monitoring activities
- I10 – Evaluative activities

**Outcome Criteria:**

- O1 – Social performance measures
- O2 – Ecological performance measures
- O3 – Externalities to other SESs

**Governance Systems (GS)**

- GS1 – Policy area
- GS2 – Geographical scale
- GS3 – Population
- GS4 – Regime type
- GS5 – Rule-making organizations
  - GS5.1 – *Number of organizations*
  - GS5.2 – *Institutional diversity*
  - GS5.3 – *Economic resources*
  - GS5.4 – *Human resources*
- GS6 – Rules-in-use
  - GS6.1 – Operational -choice rules
    - *GS6.1.1 – Stormwater ordinances*
      - *GS6.1.1.1 – Technical basis*
      - *GS6.1.1.2 – Administrative apparatus*
      - *GS6.1.1.3 – Enforcement provisions*
    - *GS6.1.2 – Stormwater utility funding scheme*
      - *GS6.1.2.1 – Price instrument*
      - *GS6.1.2.2 – Credits or fee reduction*
    - *GS6.1.3 – Stormwater management plans*
      - *GS6.1.3.1 – Operations and maintenance*
    - *GS6.1.4 – Related regulations*
  - GS6.2 – Collective-choice rules
    - *GS6.2.1 – Enforcement responsibilities*
  - GS6.3 – Constitutional-choice rules
    - *GS6.1.3 – Stormwater management plans*
      - *GS6.1.3.1 – Operations and maintenance*
    - *GS6.1.4 – Related regulations*
  - GS6.2 – Collective-choice rules
    - *GS6.2.1 – Enforcement responsibilities*
  - GS6.3 – Constitutional-choice rules
- GS7 – Property-rights systems
  - *GS7.1 – Watercourse law*
    - *GS7.1.1 – Prior appropriation doctrine*
- GS8 – Repertoire of norms and strategies
  - *GS8.1 – Diversity*
  - *GS8.2 – Risk tolerance*
- GS9 – Network structure
  - *GS9.1 – Horizontal*
  - *GS9.2 – Vertical*
- GS10 – Historical continuity

**Actors (A)**

- A1 – Number of actors
- A2 – Socioeconomic attributes
- A3 – History or past experiences
  - *A3.1 – Experimentation*
  - *A3.2 – Environmental injustices*
- A4 – Location
- A5 – Leadership/entrepreneurship
  - *A5.1 – Policy entrepreneur*
  - *A5.2 – Policy community*
- A6 – Norms (trust-reciprocity)/social capital
  - *A6.1 – Trust*
  - *A6.2 – Reciprocity*
  - *A6.3 – Social capital*
- A7 – Knowledge of SES/mental models
  - *A7.1 – Types of knowledge*
    - *A7.1.1 – Traditional ecological knowledge*
    - *A7.1.2 – Local ecological knowledge*
    - *A7.1.3 – Technical expertise*
  - *A7.2 – Mechanisms to share knowledge*
  - *A7.3 – Scale of mental models*
- A8 – Importance of resource (dependence)
- A9 – Technology available
  - *A9.1 – Ownership*
  - *A9.2 – Research support*
    - *A9.2.1 - Environmental performance*
      - *A9.2.1.1 – Stormwater management*
      - *A9.2.1.2 – Environmental "co-benefits"*
    - *A9.2.2 – Social benefits*
    - *A9.2.3 – Design and complexity*
    - *A9.2.4 – Maintenance procedures*
    - *A9.2.5 – Reliability*
    - *A9.3.1 – Capital*
    - *A9.3.2 – Operation and maintenance*
  - *A9.4 – Perceptions/attitudes*

**Resource Systems (RS)**

- RS1 – Sector
- RS2 – Clarity of system boundaries
- RS3 – Size of resource system
- RS4 – Human-constructed facilities
  - *RS4.1 - Locations*
    - *RS4.1.1 – Availability for potential facilities*
  - *RS4.2 – Functionality*
- RS5 – Productivity of system
- RS6 – Equilibrium properties
  - *RS6.1 – Frequency/timing of disturbances*
- RS7 – Predictability of system dynamics
- RS8 – Storage characteristics
  - *RS8.1 – Soil characteristics*
  - *RS8.2 – Imperviousness*
- RS9 – Location
- RS10 – Ecological history
  - *RS10.1 – Human use and disturbance*

**Resource Units (RU)**

- RU1 – Resource unit mobility
- RU2 – Growth or replacement rate
- RU3 – Interaction among resource units
- RU4 – Economic value
- RU5 – Number of units
- RU6 – Distinctive characteristics
- RU7 – Spatial and temporal distribution

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).

## 2.5 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 (U.S. EPA 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).

## 2.6 Conclusions

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.

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## Appendix 2

**Table A2.1 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[‡]** |
|---|---|---|---|---|---|---|
| **Second** | **Third** | **Fourth** | **Fifth** | | | |
| **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 | McGinnis (2011)[†] |

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| | | market dynamics and cultural change | |
| 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] |

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| 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)‡ |
| **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)† |
| RU1 | **Resource unit mobility** | Ability for resource units to move throughout the resource system |  |
| RU2 | **Growth or replacement rate** | Absolute or relative descriptions of changes in quantities (x) of resource units<br>over time (t) | Basurto et al. (2013)†, Clean Water America Alliance (2011)‡ |
| RU3 | **Interaction among resource units** | Interactions among resource units during different time periods affecting the<br>future structure of the population | Basurto et al. (2013)† |
| RU4 | **Economic value** | Value of resource units in relation to the portfolio of resources available to | Basurto et al. (2013)†, Clean |

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| | | actors | Water America Alliance (2011)‡ |
| RU5 | **Number of units** | Amount of individual resource units in resource system | |
| RU6 | **Distinctive markings** | Characteristics that can be identified in resource units and affect actors’ behavior toward them | Basurto et al. (2013)† |
| RU7 | **Spatial and temporal distribution** | Allocation patterns of resource units across a geographic area in a particular<br>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)† |

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| 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 | |
| | RS4.1 | | **Locations** | Spatial extent where facilities are constructed by actors | Perez-Pedini et al. (2005)[‡], Montalto et al. (2013)[‡], Askarizadeh et al. (2015)[‡] |
| | | RS4.1.1 | **Potential facilities** | Availability of suitable locations for potential facilities | Clean Water America Alliance (2011)[‡], Hammitt (2010)[‡], Shuster et al. (2014)[‡] |
| | RS4.2 | | **Functionality** | Degree to which stormwater management facilities achieve desired outcomes | Nowacek et al. (2003)[‡], Siglin (2012)[‡], Keeley et al. (2013)[‡], Flynn et al. (2014)[‡] |
| RS5 | | | **Productivity of system** | Rate of generation of resource units | Clean Water America Alliance (2011)[‡] , |

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|  |  |  |  | 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 |  |
|  | RS6.3 | **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 |  |
|  | RS8.1 | **Soil characteristics** | Hydrologic characteristics of soils | Nowacek et al. (2003)[‡], Clean Water America Alliance (2011)[‡], Shuster et al. (2014)[‡], Rhea et al. (2014)[‡] |

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| | | RS8.2 | **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)[‡] |
| | RS10 | | **Ecosystem history** | Past interactions that affect current actors' behaviors and stormwater management plans | |
| | | RS10.3 | **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)[‡] |

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| 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)[‡] |
| 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)[†] |
| | GS5.1 | **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)[‡] |
| | GS5.2 | **Institutional diversity** | Degree of variation represented among rule-making organizations (including public sector, private | Stockwell (2009)[‡], Hammitt |

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|  |  |  | sector, nongovernmental, community-based, or hybrid organizations) | (2010)‡, Keeley et al. (2013)‡ |
|  | GS5.3 | **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)‡ |
|  | GS5.4 | **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)‡ |
|  | GS6.1 | **Operational-choice rules** | Set of regulations or principles governing the implementation of practical decisions by individuals authorized or allowed to take these | McGinnis (2011)†, Hammitt (2010)‡ |

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| | | | actions, often as a result of collective choice processes | |
| GS6.1.1 | | **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)[‡] |
| GS6.1.2 | | **Stormwater utility funding scheme** | Premise that urban drainage systems are public systems | Debo and Reese (2003)[†], (Fletcher et al., 2011)[‡], |

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| | | | | 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 though 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)‡ |
| GS6.1.3 | | **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)‡ |

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|  |  | GS6.1.4 | **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)‡ |
|  | GS6.2 |  | **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)† |
|  | GS6.3 |  | **Constitutional-choice rules** | Set of regulations or principles governing the processes though 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)† |
|  | GS7.1 |  | **Watercourse law** | Water laws pertaining to water within a defined watercourse | Debo and Reese (2003)†, Holloway et al. (2014)‡ |

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|  |  | GS7.1.1 | **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)[‡] |
| 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)[‡] |
|  | GS8.1 |  | **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)[‡] |
|  | GS8.2 |  | **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)[‡] |

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| | GS9.1 | **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)[‡] |
| | GS9.2 | **Vertical** | Connections that link actors with other organizations across levels | Hammitt (2010)[‡], Dochow (2013)[‡], Keeley et al. (2013)[‡], Shuster et al. (2008)[‡] |
| GS10 | | **Historical continuity** | The length of time for which a particular form of governance has been in place | McGinnis and Ostrom (2014)[†] |
| **Actors (A)** | | | Attributes of the individuals or groups that interact with resource units | 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)[‡], |

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| | | | | 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)[‡] |
| 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)[‡] |

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|  | 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 | McGinnis (2011)[†], Shandas |

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| | | | | with others who have cooperated with them in previous encounters. | 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 | |
| | | A7.1.1 | **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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| | | A7.1.2 | **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)[‡] |
| | | A7.1.3 | **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)[‡] |

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| 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)‡ |
|  | A9.2.1 |  | **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)‡ |

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| | A9.2.2 | **Social outcomes** | Extent of social outcomes associated with a technology | Clean Water America Alliance (2011)[‡], Kondo et al. (2015)[‡] |
| | A9.2.3 | **Complexity of design** | Degree to which technology designs are easily replicable | Nowacek et al. (2003)[‡], Roy et al. (2008)[‡], Hammitt (2010)[‡], Dochow (2013)[‡] |
| | A9.3.4 | **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)[‡] |
| | A9.2.5 | **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)[‡] |

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| A9.3.1 | **Capital** | Fixed, one-time expenses related to the implementation of a technology | Winz et al. (2014)[‡], Thurston et al. (2010)[‡], Cote and Wolfe (2014)[‡] |
| A9.3.2 | **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)[‡] |

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| 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)[‡] |
| 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)[‡] |

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| 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 | McGinnis and Ostrom (2014)† |

| | | | |
|---|---|---|---|
| | | determinants of many potential exogenous influences | |
| ECO1 | Climate patterns | Recurring characteristics of the statistical distribution of weather over an extended period of time | Clean Water America Alliance (2011)‡ |
| ECO2 | Pollution patterns | Recurring characteristics of contaminants that cause adverse effects | Lassiter (2007)‡, Hammitt (2010)‡ |
| ECO3 | 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

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# Chapter 3 Transforming a waterscape: Application of the social-ecological framework to assess the evolution of stormwater governance in Onondaga County, New York, USA

## 3.1 Abstract

The social-ecological systems framework provides a classification structure of attributes and processes that are common to social-ecological systems. This paper illustrates the use of this framework to identify key attributes and processes related to the adoption of a municipal green stormwater infrastructure program. A case study on the urban stormwater social-ecological system in Onondaga County, New York, examines the factors related to transformational changes within local stormwater management planning. Important changes occurred in the program goals, political leadership, economic opportunities, and knowledge sources used in stormwater program design. These changes are discussed within the context of institutional power relations and governance characteristics. The findings make explicit the importance of integrating diverse stakeholder goals and adaptive decision making to address urban water management challenges.

## 3.2 Introduction

Historically, stormwater management plans in the U.S. have favored gray infrastructure, or technologies that either enhance or supplement existing sewer infrastructure. In many communities, urban stormwater objectives are changing in response to socio-political drivers (Brown et al. 2009, Moglia et al. 2012). Alternatives to gray infrastructure include an array of technologies broadly referred to as green stormwater infrastructure (GI), also known as low impact design. GI is designed to protect, restore, or mimic the natural hydrology of a site. Examples of GI include green roofs, rain gardens, street trees, and permeable pavement. It has been theorized that GI can improve social-ecological system resilience through improved urban temperature regulation, air quality management, enhanced biodiversity, and increased recreational values (Tzoulas, et al., 2007). Using solely gray stormwater infrastructure and neglecting GI has been linked to negative social-ecological outcomes such as high economic costs, environmental justice issues, and an inability to accommodate climatic change (Novotny et al. 2010, Pyke et al. 2011, Wendel et al. 2011, De Sousa et al. 2012).

Hundreds of communities are finding ways to integrate GI into local stormwater infrastructure systems, including Onondaga County, New York, USA. For decades, Onondaga County's stormwater management plans implemented only gray infrastructure technologies to reach strict ecological outcomes as dictated in a regulatory compliance order, resulting in disapproval and protest from multiple stakeholder groups. In 2009, these plans changed significantly with the addition of GI projects and redesign of unfavorable planned gray infrastructure projects. The revised plans explicitly acknowledged the effects of various stormwater infrastructure practices have on both the local residents and broader watershed ecology.

As more communities seek to avoid negative social-ecological outcomes related to stormwater management planning, there is a need to more easily relate attributes and configurations of urban stormwater systems to particular outcomes. Frameworks can help in the accumulation of knowledge from empirical studies and the identification of universal elements and relationships that lead to particular outcomes. The social-ecological system (SES) framework gives equal attention to the biophysical and ecological foundations of institutional systems that influence social-ecological decision-making processes (Ostrom 2007, 2009). We hypothesize that the SES framework can aid researchers in diagnosing challenges related to the stormwater management and exploring strategies to avoid negative social-ecological outcomes. This paper presents a case study on the evolution of stormwater management practices in Onondaga County. An urban water management SES framework (Flynn and Davidson, 2016) is used to explore the interactions between key SES attributes that led to the adoption of new stormwater management plans. Two key objectives of this research are (1) to explore the evolution of SES attributes that led to GI adoption in the case study, and (2) to provide an illustrative case of positive environmental transformation that connects issues of institutional power, environmental injustice, and social exclusion using an adapted SES framework. Findings from this analysis are used to explore broader changes of institutional power relations and adaptive governance characteristics from the case that are not explicitly defined within the SES framework.

## 3.3 Background

Wicked water management problems are related to collective action dilemmas, in which actors must overcome short-term individual incentives to achieve socially preferred outcomes in the management of common pool resources (Ostrom et al. 1994, Adams et al. 2003). To appreciate this complexity, it is helpful to consider a water management system as an example of a social-ecological system (SES), defined by both its social components, such as water users, policymakers, governing institutions, and cultural relations to local water supplies, as well as its ecological components, such as water flows (e.g., precipitation, groundwater, surface water, wastewater, stormwater, etc.), climate, and topography. Similarly, the concept of a water landscape, or "waterscape," has been used to explicitly acknowledge the interacting linkages between social and environmental attributes of water, power, and governance within water management systems (Swyngedouw 1999, Harris 2006, Loftus 2009, Loftus and Lumsden 2008, Perreault et. al 2012). Within this waterscape concept, attributes such as water use and rights are often considered as expressions of power relations.

Numerous SES attributes have the potential to affect the patterns of collective action and outcomes related to sustainable resource governance (Agrawal 2001, Ostrom 2009). Because urban water management SESs involve a vast number and diversity of stakeholders, solutions to overcoming collective action problems in these contexts often require an emphasis on institutional interactions and decisions, rather than those of individual actors. Many scholars have explored the effects of institutional characteristics and arrangements on large scale water management systems (Blomquist et. al 2004, Kerr 2007, Meinzen-Dick 2007, Schlager and Blomquist 2008, Schlager and Heikkila 2011).

Several conceptual frameworks aim to identify the complex attributes of common pool resource systems. The SES framework bridges disciplinary and methodological boundaries by providing classification of important SES attributes and relationships (Ostrom 2007, Ostrom 2009, McGinnis and Ostrom 2014). It draws on an understanding of individual actors, governance systems, resource units, and resources systems as interacting elements. Revisions to the SES framework continue to develop as new cases and theoretical insights address limitations of the framework (Basurto et al. 2013, Epstein et al. 2013, Vogt et al. 2015). Past common pool resource and SES research has faced criticism for inadequately addressing how power, politics, and inequality affect governance processes (Goldman 1997, Agrawal 2014). The SES framework may assist in the analysis of institutional power; because it is not explicitly defined within the framework, power must be operationalized using select attributes (Epstein et al. 2014).

## 3.4 Methods

The overall empirical research and analysis approach to the study is based on a case study research design, as the context of stormwater management transformations in Onondaga County between 1998 and 2009 is viewed as a major part of the study (Yin 2013). A blend of descriptive and exploratory case study designs are used to both develop a complete description of the transformation with its context and to develop causal inferences on why important changes took place (Hancock and Algozzine 2015; Bryman 2015). Triangulation methods, using document analysis and interviews, were used to identify important factors that acted as both inputs and outputs of action situations related to stormwater management decisions in Onondaga County between 1998 and 2009.

Data for this study were collected through several iterations. Regulatory orders that stipulated the establishment and amendment of Onondaga County's stormwater management program were collected as the preliminary document archive. Initial coding of these documents assisted in identifying a purposeful sample of interviewees and informed the production of an interview guide. The interview guide was designed to collect information regarding the stakeholders' knowledge and attitudes that were associated with the evolution of local stormwater management plans. A semi-structured format allowed interviewees to recount events from their own perspective. A "snowball sampling" approach (Biernacki and Waldorf 1981) enabled both the expansion of the interviewee sample and the document archive for this case. At the closing of all interviews, participants were asked to suggest other individuals or organizations relevant to the case, as well as documents that would provide insight to the events related to GI adoption. This approach carries a risk of reinforcing the silencing of stakeholder perspectives due to the limited social network of initially chosen interviewees. This risk was offset by independently reviewing documents for additional interviewees and ensuring professionally diverse interviewees were represented in the sample. In total, 11 in-person interviews were conducted with government officials, community group representatives, and water quality researchers.

An SES framework adapted for urban stormwater management (Flynn and Davidson, 2016) is used to describe and organize these findings. Identifying what SES attributes are linked to particular outcomes is complicated by the dynamic interactions and evolution of multiple variables. Cole et al. (2014) address this problem by analyzing variables as *pre-existing conditions* and *significant outcomes and effects* of adjacent action situations. A similar process was used in this study to describe the findings in three analytical stages: pre-existing conditions during a traditional infrastructure stage (Stage 1), a transition stage when multiple adjacent actions took place (Stage 2), and the significant outcomes of the early GI implementation stage (Stage 3).

Results from the SES framework application are used to highlight dynamic power relations that characterize this case. Epstein et al. (2014) propose a four-step process for testing the effect of power within an SES study: (1) adopt relevant definitions or theories of power, (2) classify chosen definitions in terms of one or more SES framework attributes, (3) choose how to operationalize or measure those attributes for empirical analysis, and (4) analyze the effects of measured attributes on the outcomes of interest. Institutional power is considered in this study, as many theoretical connections to institutional power emerged during the data analysis process of this study. Institutional power can be operationalized at several levels of rule-making, as defined within the SES framework. Operational-level rules dictate what, when and how resources are accessed and used (or in the case of stormwater, conveyed and collected), whereas collective-choice rules provide a framework for how and by whom operational rules are created and modified. Thus, rules that define and constrain the operational activities of SES actors are established by collective-choice processes (McGinnis and Ostrom 2014). Several SES framework attributes from Table 2.1 are used to examine the institutional power relations at the operational and collective levels, including actors' history of use (A3), participation of organizations in rule-making processes (GS5), and their perceived fairness of operational rules (GS6.1) and collective-choice rules (GS6.2).

## 3.5 Results

### 3.5.1 Stage 1

Onondaga County's political boundaries contain at least a portion of four lakes and eight sub-watersheds that drain to one of two major watersheds[2]. The Onondaga Lake watershed covers 738 square kilometers in Central New York and drains to Onondaga Lake, located along the edge of the City of Syracuse, which is the largest city within Onondaga County. Combined sewers, which convey both wastewater and stormwater, comprise approximately 58% of the sewer system in the city. While the City of Syracuse is responsible for the private sewer laterals, the County government owns and operates the large combined sewer trunk lines that convey city sewage to the County's wastewater treatment plant. During wet weather, combined sewer overflows (CSOs) release a flow of untreated sanitary sewage and stormwater to the lake's tributaries.

Onondaga Lake is the central ecological feature of an urban water SES that has experienced multiple environmental crises and transformations throughout the 20th century due

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[2] A map of watersheds in Onondaga County is available here: http://www.ongov.net/planning/documents/map_gallery/Watersheds%20in%20Onondaga%20County.pdf

to the large contribution of municipal and industrial wastes to the lake. Nutrient-rich treatment plant effluents led to a hypereutrophic state in the lake, resulting in high populations of phytoplankton, increased turbidity, extended periods of hypolimnetic anoxia, and a decrease in ecosystem function (Effler and O'Donnell 2010, Canale and Effler 1989) Drastic changes in lake ecological regimes led to socioeconomic shifts. For instance, during the early half of the 20th century, thriving fisheries and resort industries that had operated since the 1800s slowly died out as the lake's water quality deteriorated. Swimming was banned in 1940 due to elevated bacteria counts and poor water clarity, and all fishing was banned in 1972 due to mercury contamination (Thompson 2002, Landers 2006). CSOs have been a persistent issue in restoration of the lake. Originally, the sewer system included over 90 CSO points that discharged an average of once per week.

In the U.S., CSO water management policies are designed around federal and state regulations which aim to improve urban water quality and prevent human health risks. The passage of the 1972 Clean Water Act by the U.S. Congress created a national framework for establishing water quality standards and discharges to surface waters, requiring industries and municipalities to implement pollution control programs (Clean Water Act, 1972). Under this framework, municipal CSO abatement programs focus on infrastructure projects that reduce stormwater flows within the combined sewer system (e.g., sewer separation, storage tanks for CSO volume), and enhance water quality (e.g., additional or enhanced treatment facilities).

Onondaga County's Department of Water Environment Protection began implementing stormwater management plans for CSO control after a 1988 lawsuit. The Atlantic States Legal Foundation, a local nonprofit, filed the lawsuit against Onondaga County, alleging that the discharges from the wastewater treatment plant and CSOs were in violation of the Clean Water

Act. In 1989, Onondaga County entered into a judgment of consent with Atlantic States Legal Foundation and the New York State Department of Environmental Conservation (NYSDEC), requiring the County to execute a series of studies and develop a CSO management plan. In 1990, the Onondaga Lake Management Conference was established and was tasked with developing and coordinating the implementation of a comprehensive restoration, conservation, and management plan for Onondaga Lake. The organization consisted of six voting members, each of which was a governmental organization at either the federal, state, or local level. Studies and negotiations of the compliance plans ensued until an amended consent judgment as executed in 1998. At the time, existing gray infrastructure solutions captured or eliminated about 74% of the total annual CSO volume. The 1998 amended consent judgement required the annual CSO volume capture rate to increase to 85%, along with increased removal of floatable waste as well as more stringent water quality standards for bacteria in the lake by 2012. Approved technologies for the plan included multiple regional treatment facilities, which would provide primary treatment to disinfect CSOs. The Midland regional treatment facility was the largest proposed facility and was to be built in the Southside neighborhood, home to a high proportion of low income and minority residents near Onondaga Creek, a main tributary of Onondaga Lake.

### 3.5.2 Stage 2

In 1999, the Onondaga Lake Partnership replaced the Onondaga Lake Management Conference, though its voting membership comprised of the same six governmental organizations. The exclusion of many stakeholder groups from the planning and decision-making processes resulted in an opposition to the proposed gray infrastructure projects, most notably among members of Onondaga Nation, a sovereign member of the Haudenosaunee Confederacy of native nations, and the residents of the Southside neighborhood of Syracuse. Onondaga Nation retains a section of its original territory within Onondaga County south of the City of Syracuse. As Onondaga Lake has been considered a sacred site by the Onondaga people for over a thousand years, Onondaga leaders argue that the infringement of their nation's traditional resource use rights and degradation of the lake have harmed their people's cultural, economic, physical, emotional, and spiritual well-being (Perreault et al., 2012). Onondaga Nation remains committed to fulfilling its vision of cooperative resource management and environmental stewardship of the lake to restore natural hydrological cycles (Onondaga Nation 2010). Despite the filing of a Land Rights Action in 2005, no formal recognition of these traditional rights has yet been made. Southside residents viewed the Midland treatment facility as a stigmatizing environmental injustice. In 2000, a nonprofit organization, the Partnership for Onondaga Creek (POC), was formed and began organizing protests, lobbying policy makers, and developing alternative solutions to the Midland treatment facility, such as increasing the use of underground storage technologies. The POC began to collaborate with the Onondaga Nation and other stakeholders to form a policy community around alternative stormwater management solutions (Tauxe 2011). The alternative plans proposed by the POC gained the support of most other stakeholders including the City of Syracuse. The City refused to sell property to the County government for the Midland treatment facility, citing concerns from residents who opposed the plan (Weiner 2002). Claiming a historical and legal interest in Onondaga Creek, Onondaga Nation was granted admission to the stormwater planning negotiations. With the support of the Onondaga Nation, the POC was also admitted as a party to the negotiations (Adams 2003). Ultimately, the County ended negotiations on the Midland treatment facility location and gained a court order in 2002 to take the City land. The Midland treatment facility construction resulted in several social damages and injustices in the Southside community (Lane and Heath 2007, POC 2006). An “anti-treatment facility” sentiment grew throughout the County along with a lack of trust in the stormwater management decision makers.

Several communities in the U.S. began to experiment with GI technologies in the 1990s. The success of early projects led to an influential 2006 report that stimulated national groups to promote GI, including the U.S. Environmental Protection Agency (EPA) in 2007 (Kloss et al. 2006, U.S. EPA 2007) Around this time, the POC, Onondaga Nation and other local groups and stakeholders in Onondaga County began to develop alternative plans in which GI would replace unfavorable technologies such as regional treatment facilities (Knauss, 2010). However, the pre-existing County leadership made it difficult for new plans to gain approval. Onondaga County’s previous stormwater management plans were limited by a governance network with long standing officials who supported only gray infrastructure solutions. This network had developed a high level of interconnectivity between engineering firms and the County and State governments which supported established stormwater management solutions (Tauxe 2011).

A local politician who was familiar with the backlash against regional treatment facility sentiment of local residents and the alternative plans proposed by the POC began a campaign for County Executive in 2007. During this time, she reached out to Onondaga Nation and POC to better understand their goals for stormwater management. She also learned of scientific studies that suggested treatment facility would not provide a comprehensive solution to reduce bacteria loadings to the tributaries of Onondaga Lake. Shortly after taking office in January 2008, she obtained a moratorium on construction of a regional treatment facility that was to be built in downtown Syracuse. Any changes to the program would require approval by prosecuting parties of the original consent judgment (the NYSDEC and Atlantic States Legal Foundation) and a federal judge. Working together with these parties as well as the POC and Onondaga Nation, the

County received permission to evaluate alternative engineering solutions for CSO management. Several committees were created by the County Executive to consider how to move forward. The committees included representatives from the Onondaga Nation, POC, and other formerly excluded stakeholder groups. Each committee made recommendations to the County Executive's administration regarding revised management plans, though the Executive retained the authority to decide on the final plans.

### 3.5.3 Stage 3

The committees' findings were incorporated into a revised amended consent judgement in November 2009, requiring Onondaga County to use both gray infrastructure and GI in its stormwater management plans. Previously, several municipalities throughout the U.S. had integrated GI into consent decrees as supplemental environmental projects. However, Onondaga County's amended consent judgement represented the first time in the U.S. that GI was listed as a direct legal requirement in the reduction of CSOs (Garrison and Hobbs 2011). Revised gray infrastructure projects were also required, including a large storage tank in place of the downtown regional treatment facility. The gray infrastructure projects completed between 1998 and 2009 increased the annual CSO volume capture rate to an estimated 84.6% on a system-wide basis. The 2009 judgement stipulated a higher annual CSO volume capture rate of 95%, up from the target of 85% stipulated in the 1998 judgement. This was agreed upon due to modeling estimates suggesting that had all original planned gray infrastructure project been built, they would have captured 95% annual CSO volume. Thus, the changes made in 2009 would also need to reach this level.

The revised plans were approved not only because replacing select gray projects with GI would be less intrusive, but also because they were estimated to save Onondaga County more than $20 million in meeting regulatory requirements. The revised stormwater program budget of approximately $400 million set aside $78 million specifically for GI projects, which reflects a reallocation of funds originally designated towards the regional treatment facilities. Aside from cost savings, the rapid development of GI projects throughout the County would not have been possible without additional economic opportunities developed by County officials. The majority of funds for the GI program are financed through independently-secured bond debt. This is due to a loan and bond process that favors large centralized projects such as gray infrastructure (Flynn et al. 2014). Additional funding originated from grant programs for GI projects that did not exist prior to 2009. Another unique economic opportunity is the development of a public-private partnership program for GI, which set aside funds to offer reimbursement incentives to businesses and non-profits to install GI on their property.

### 3.5.4 Application of Urban Stormwater SES Framework

Multiple SES framework attributes were identified as key factors that shifted over the course of the three transformation stages. These variables are listed in Figure 3.1, beginning with S1 and S7 and continuing down to O2. Note that most variables experienced a change between Stage 1 and Stage 3 as indicated in the figure. For example, for variable S1, there was no grant funding for green infrastructure during Stage 1, but grants became available by the time of Stage 3. Several key attributes that were identified did not change during the time period explored and thus acted as system parameters, which are listed as bolded attributes in Stage 1. All Stage 1 attributes set conditions for the principal activities that are listed in the figure under Stage 2, beginning with I4 and continuing down to I10. The activities are organized to convey a progression of the types of activities and interactions that occurred over time. While the significant outcomes in variables are listed in Stage 3, many of these changes took place

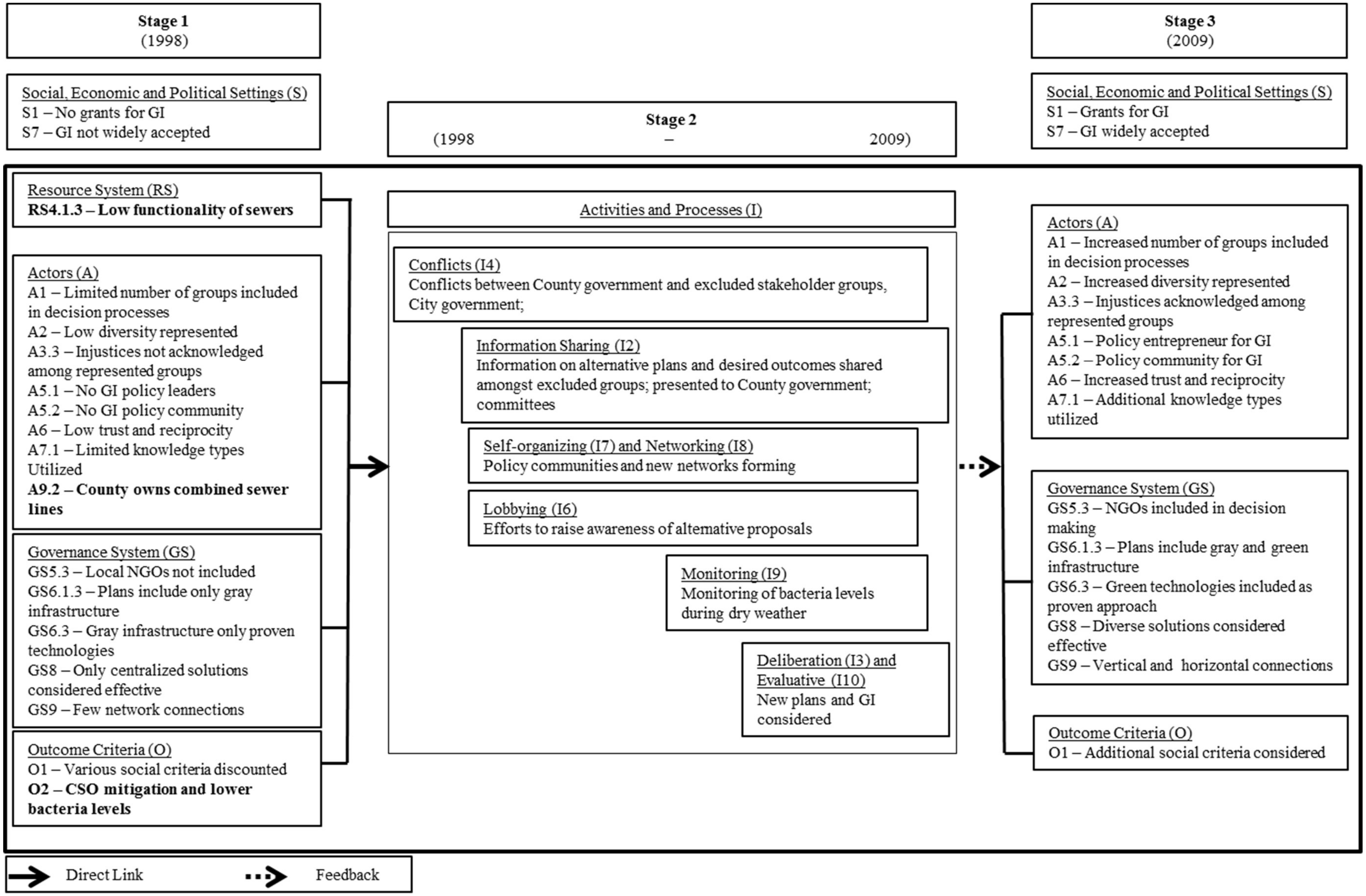

**Figure 3.1 Evolution of Onondaga County's Stormwater SES, 1998-2009. Bolded items in Stage 1 indicate parameters that did not change between Stage 1 and 3**

gradually throughout Stage 2 as a result of feedback loops and interactions during various activities and processes. The variables describing the “Actors” category depict changes related to the individuals or groups that are involved in rule-making processes related to Onondaga County’s stormwater management plans.

The norms of the pre-existing political administration in Onondaga County’s governance network included long standing actors who were accustomed to implementing only gray infrastructure solutions for CSO compliance (GS8), leading to conflict (I4) with excluded stakeholder groups that were dissatisfied with these solutions. As these stakeholder groups began to share information (I2) and network (I8), they self-organized (I7) into a policy community (A5.2) as they lobbied (I6) to support alternative stormwater management plans. A policy window, or an opportunity for a policy proposal to move onto the political agenda, can be opened when two key attributes are present: an alternative policy proposal and a policy entrepreneur, or an individual who is willing to introduce and advocate for policy alternatives (Kingdon 1995). The 2007 election for County Executive can be interpreted as the major impetus for the opening of a policy window for a new stormwater management program featuring extensive use of GI. The new County Executive acted as a policy entrepreneur (A5.1) by collaborating with the policy community of excluded stakeholders in support of GI and seeking additional sources of knowledge (A7.1). The multi-stakeholder steering committees included a greater number of actors in decision-making processes (GS5.1), including a diverse set of formerly excluded stakeholder groups that had experienced a history of environmental injustices (GS5.2, A3.2). This integration of stakeholders within these committees formalized a stronger horizontal network structure (GS9.1) that allowed for information sharing and deliberations (I2, I3) between the County government and key stakeholders. This collaboration led to increased trust and reciprocity (A6) and enhanced social outcomes in the County's stormwater management plans (O1). Various social performance measures can be used to assess the value of the County's revised stormwater management plans. The use of GI created the potential for additional "co-benefits" (A9.3.1.2), such as increased recreational value and improved health statistics (Tzoulas et al. 2007). Onondaga County's GI efforts include goals to enhance social benefits of infrastructure projects through job programs, strategic project placement, and avoided social costs associated with additional regional treatment facility and pipeline projects. Both the environmental and social outcomes of GI can enhance the long-term social well-being of communities in Onondaga County, though these benefits will be realized over time periods beyond Stage 3 of this analysis.

Increased knowledge (A7.1) from monitoring efforts (I9) revealed that the proposed gray infrastructure solutions would not provide a comprehensive solution to Onondaga County's environmental problems, despite achieving the desired CSO volume control. A local environmental non-profit organization conducted a study in 2007 that revealed high levels of bacteria in tributaries flowing into Onondaga Lake during dry weather, suggesting that there were sources of contamination other than CSOs leading to non-compliance of state standards for bacteria (Hughes 2008). Because regional treatment facilities would provide only primary disinfection treatment to manage bacteria loadings from CSOs, they were deemed inadequate to reach compliance due contamination sources associated with the existing sewer infrastructure (RS4.2).

The original consent judgement represents a set of constitutional rules (GS6.3) for stormwater management. This judgment stipulated that Onondaga County, as the owner of the central combined sewer lines (A9.2), was required to achieve the ecological performance measures (O2) of capturing or eliminating CSO volumes and reducing bacteria levels in Onondaga Lake. The desired ecological performance outcomes did not change between 1998 and 2009. However, the constitutional rules regarding how the CSO volumes would be mitigated did change. The 1998 judgement included a conditional statement that only if there are "proven technologies available that could satisfy the requirement of the amended consent judgement in a less costly manner" could the agreed upon plans be revised. The 2009 judgement changed the constitutional rules of how CSO volume could be managed, acknowledging that GI technologies would be utilized by the County to achieve the CSO control requirements The revised plans represent a change in the operational rules (GS6.1.3), dictating the gray and green technologies that would be implemented.

Two key attribute changes that are reflected in the acceptance of GI in the revised consent judgement plans include the change in technological settings of accepted stormwater management technologies (S7) and accepted norms of the governing system (GS8). Technology settings refer to the broader set of established technological solutions that are generally considered to be effective stormwater management practices. While GI technologies had been used in several municipalities of the U.S. in the 1990s, such as Portland and Seattle, they were not nationally recognized in the U.S. as an effective stormwater management practice until the U.S. EPA's promotion of GI in 2007 (U.S. EPA 2007). This change in mindset of the EPA, a national rule-making organization, acted as an exogenous system setting change and provided momentum to local stakeholders in Onondaga County to develop stormwater plans which included GI. New economic opportunities, including public-private partnerships as well as federal and state assistance (S1), made GI cost effective against gray infrastructure alternatives.

### 3.5.5 Institutional Power

The application of the SES framework identified multiple system attributes and interactions that shifted over the time period examined in this case study. This identification process leaves some questions about the heterogeneous interactions between actors and their desired outcomes. For instance, several groups of actors held differing perceptions of justice regarding Onondaga County's original stormwater management plans, as well as varying degrees of participation in decision-making processes. To explore this heterogeneity, we consider the interactions among several SES framework attributes as dynamic institutional power relations. Perreault et al. (2012) analyze the multiple modes of environmental injustices that arose from uneven power relationships in water resource management in Onondaga County. Their study provides a detailed account of the historical and geographical perspectives of the Onondaga Nation and Southside residents, and uncovers the multi-scale nature of environmental injustices related to water resources in Central New York. The results from our study build on these findings with insights on the institutional power dynamics and arrangements within the case of stormwater management planning between 1998 and 2009.

One approach to measuring power is to assess differences in the interests of actors who are involved in rule-making processes at various levels, and the interests of those who are not. Under the ruling of the amended consent judgement, the collective-choice rules (GS6.2) stipulate that the power to negotiate the stormwater management plans is held by the County government and the prosecuting parties (NYSDEC and Atlantic States Legal Foundation). The County Executive holds a high level of power in the County government, in that this actor can unilaterally make decisions regarding operational rules for stormwater management (GS6.1). The power relations in Stages 1 and 2 connect to the first two faces of power as defined by Steven

Lukes (2005). According to Lukes's second face of power, an imbalance exits when groups are prevented from representing their interests in political processes by virtue of the actions of another group. This imbalance is found in Stage 1, as the Onondaga Nation and POC perceived the stormwater management plans as unjust and insufficient, and both groups were excluded from negotiations during inputs to rule-making (GS5). Early in the transition period of Stage 2, a shift in the second face of power dynamics occurred as the both parties were invited into voice their concerns during the negotiations on the sale of City land to build the Midland Treatment Plant. It should be noted that while the POC and Onondaga Nation participated in negotiations during Stages 2, their legitimacy to participate and effect change in the CSO management planning was never formalized. However, the County ultimately moved forward with the original plans, using their designated power from the amended consent judgement to do so. These circumstances can be understood as an exertion of Lukes's first face of power, such that groups participating in collective choice decisions fail to produce rules that align with the interests of all groups. Thus, the shift in the second face of power was not enough to effect change in the County's plans. The described imbalances in both Luke's first and second faces of power and resulted in resistance to institutional change and undesirable social-ecological outcomes present in Stage 1 and much of the conflict throughout Stage 2.

Another approach to understanding forms of institutional power is to assess the activities and processes that create institutions that are resistant to change. One such process is a positive feedback of increasing returns along a particular decision pathway, which privileges some groups with a greater share of benefits and institutional control that enhances their bargaining power (Arthur 1989, North 1990, Pierson 2000). The individual that held the position of County Executive during Stage 1 and most of Stage 2 was, at the time, the longest running county executive in New York State, holding the office for 20 years. During this time, many of the consulting engineering firms had personal connections to the County administration and faced lucrative opportunities to design and implement stormwater management projects (POC 2006, Tauxe 2011). This feedback between the County's plans and engineering solutions ended after a change in the individual attributes of the elected County Executive (A3, A6). The 2008 incoming County Executive had experienced the early planning negotiations as a previous member of the Syracuse City Common Council, and she had opposed many of the County's plans. During her campaign, she sought guidance from the POC and Onondaga Nation to develop a strategy for alternative proposals. With her election, the shift in the norms of the County Executive reduced the difference between the goals of the County and other stakeholder groups.

### 3.5.6 Adaptive Governance

The institutional power dynamics in this case can be understood within the context of evolving environmental governance processes that shaped multiple SES outcomes. Onondaga County's revised stormwater management approaches embody many characteristics of adaptive governance (Flynn et al. 2014). Adaptive governance is defined as the range of interactions between actors, networks, organizations, and institutions emerging in pursuit of a desired state for SESs (Chaffin et al. 2014). This collaborative approach to governing SESs is often associated with an increased capacity to adapt to changing social and biophysical circumstances including shocks and surprises (Dietz et al. 2003, Folke et al. 2005). Two key characteristics of adaptive governance are a polycentric governance structure, or a system in which political power or legitimacy is dispersed to separate organizations with overlapping jurisdictions that do not stand in hierarchical relationship (Skelcher 2005, Huitema et al. 2009); and adaptive management strategies, in which actors build and make continuous use of SES knowledge through experiments and monitoring efforts to inform policy (Holling 1978, Brunner et. al 2005, Folke et al. 2005).

In Stage 1, the institutional arrangement of Onondaga County's stormwater governance system consisted of a limited number of governmental organizations (GS5.1, GS5.2) operating under a hierarchical structure of rule-making (GS9.2). The Onondaga Lake Partnership's original mission was to act as a bridging organization by coordinating stakeholders, activities, and information related to watershed management projects. Between 1999 and 2009, the Onondaga Lake Partnership increased its diversity of member organizations in outreach and project committees; however, the power for decision-making remained with the government organizations in the executive committee, and little progress was made in legitimizing the concerns of multiple stakeholder groups.

Adaptive governance emergence is often initiated by a crisis or release event in an SES (Chaffin et al. 2014) and is fostered by individual leadership and trust building among stakeholders at the local level (Olsson et al. 2004, Folke et al. 2005, Olsson et al. 2007). The 2008 election of a new County Executive released past feedback mechanisms of institutional power. Similar to a policy window, a "window of opportunity" for adaptive governance can be opened when shadow networks and key leaders come together (Olsson et al. 2006). The policy community formed by the POC and Onondaga Nation can also be understood as a shadow network, or an informal collection of individuals or groups without rule-making power. The 2008 planning committees formed by the County Executive created formal institutional arrangements for this shadow network and other stakeholders to interact, share knowledge, and build trust. These committees grew into a polycentric governance structure of multiple formal partnerships between Onondaga County and local nongovernmental and community organizations (GS5.1, GS5.2), thus enhancing the local horizontal network for stormwater governance (GS9.1). For example, the Environmental Finance Center at Syracuse University, a university-based organization that promotes the development of sustainable communities and intergovernmental cooperation, was tasked with leading education and outreach efforts for GI projects in Onondaga County. In 2013, the Onondaga Lake Partnership transitioned into a more inclusive bridging organization called the Onondaga Lake Watershed Partnership, operating as a neutral information clearinghouse for watershed dialogue and decisions with membership open to all watershed stakeholders.

The changes in the stormwater management institutional network created opportunities for adaptive management practices, particularly related to the continuous incorporation of new knowledge into management decisions. Beginning with the 2008 planning committees, stakeholders were able to share knowledge and negotiate a common vision for stormwater governance.  Several long-term monitoring efforts have existed to collect data on the Onondaga Lake watershed, some of which are commissioned by Onondaga County. Additional scientific studies conducted by nongovernmental organizations first provided an impetus for the County to consider management solutions beyond regional treatment facilities. The 2009 amended consent judgement set up additional monitoring efforts, where new data are used to evaluate and modify stormwater management models. Annual reporting requirements are used to determine compliance with ecological outcomes, as well as to adapt stormwater infrastructure plans as new information is obtained. The Onondaga Lake Watershed Partnership works to continuously gather and facilitate input from stakeholders to develop a shared community vision for the restoration of the Onondaga Lake watershed.

## 3.6 Conclusions

An adapted SES framework was applied to the evolving stormwater management practices in Onondaga County, NY. This aided in the identification of the social and ecological factors that affected the decision to adopt GI projects beginning in 2009. The dynamic nature of these factors was considered by organizing the findings in three stages: pre-existing conditions during a traditional infrastructure stage (Stage 1), a transition stage when adjacent actions took place (Stage 2), and the outcomes and effects of the early GI implementation stage (Stage 3). Several actions and interactions were determined to be critical in the transition to GI adoption, including ecosystem monitoring, knowledge sharing, and lobbying efforts. Multiple SES attributes shifted throughout the transition, including the governance network structure, program goals, economic incentives, and the broader technological mindset for stormwater management. Select attributes were used to examine the institutional power relations and adaptive governance characteristics within Onondaga County's stormwater governance network.

The application of the SES framework to the evolving stormwater management practices in Onondaga County highlights the combination of SES attributes associated with a transition towards more sustainable stormwater governance practices. This transition is primarily understood through the examination of the social dynamics and political ecology of urban stormwater management that are embedded in the decision-making processes for stormwater infrastructure. In the case of Onondaga County, the interactions among actors, particularly among a policy community and policy entrepreneur for GI, were critical to the adoption of a GI program. The level of local leadership efforts to create a set of new common goals has been pinpointed as a critical factor in the adoption of GI in other U.S. communities (Hammitt 2010, Madden 2010), as well as the emergence of adaptive governance practices (Österblom and Folke

2013, Shuster and Garmestani 2015). Knowledge related to ecological system attributes, in particular the functionality of existing infrastructure systems, was found to affect stakeholders' conceptualization of the urban stormwater SES and which management practices would achieve desired ecological outcomes. The revised stormwater governance system represents a shift towards a more adaptive governance approach that includes multiple stakeholder perspectives, which may lead to more sustainable outcomes for the Onondaga Lake SES.

Certain limitations to these findings should be addressed. Firstly, conclusions drawn from any singular case study are limited. Further, data for this case study includes stakeholder interviews, which may be biased due to personal memory or opinion. Additionally, the adoption of a GI program does not necessarily imply that meaningful changes have taken place across an urban stormwater SES and may lead to other environmental justice issues (Wolch et al. 2014). Thus, the acknowledgment of past environmental injustices does not suggest that future injustices will be avoided. When analyzing urban water SESs, defining the outcomes of interest will likely determine which variables are most pertinent, or how certain variables are interpreted. Finally, the conclusions do not suggest that underlying power dynamics or issues of marginalization have been overcome by the reforms of stormwater management plans or governance structure. Rather, they signify a shift towards more open and adaptive decision-making processes. As many governments are facing challenges that limit their ability to regulate and maintain urban common pool resources, models of adaptive governance could provide more inclusive, equitable, and sustainable institutional alternatives.

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# Chapter 4 An assessment of sustainable stormwater system planning in the United States

## 4.1 Abstract

Improvements to stormwater management infrastructure systems are a critical social and environmental need in most municipalities of the U.S., particularly those with combined sewer systems. This study examines the adoption of sustainable stormwater management initiatives in the U.S., with a focus on green stormwater infrastructure program adoption in large combined sewer municipalities. Results from surveys of municipal leaders are incorporated into a framework that identifies significant variables that influence municipal green infrastructure program adoption. A hurdle model is used to assess the factors that influence management authorities' decision to adopt green infrastructure programs, and the factors associated with the extent of program adoption. We find that the decision to adopt a green infrastructure program is strongly driven by the population size and precipitation event characteristics of a municipality. The extent of program adoption is shown to be additionally driven by municipal socioeconomic characteristics, including residents' political preferences, median household income, and unemployment rate.

## 4.2 Introduction

Municipal wet weather sources of pollution are among the greatest contributors to modern water quality impairment, aquatic ecosystem degradation, and stream function damage (National Research Council, 2009). Throughout the past century, urban stormwater management systems in the U.S. have expanded vast networks of centralized subsurface conveyance technologies with end of pipe treatment to remedy surface water impairments. Most current stormwater regulations favor the continued use of these traditional or gray infrastructure systems that either enhance or supplement existing sewer infrastructure. Gray infrastructure engineering solutions are designed to efficiently handle large amounts of urban runoff volumes. However, they are associated with multiple societal costs, including high economic costs, negative community health effects, and, depending on the technology, harmful environmental effects. Furthermore, gray infrastructure stormwater management technologies encourage the continued development of impervious urban infrastructure, exacerbating the source of most urban stormwater problems. Many researchers have pointed out that this current paradigm for urban stormwater management is neither sustainable nor resilient enough to accommodate climatic change (De Sousa et al., 2012; Novotny et al., 2010; Pyke et al., 2011).

To decrease the reliance on inefficient centralized treatment systems, distributed systems of green infrastructure (GI) have been adopted in many U.S. metropolitan areas. GI is designed to protect or restore the natural hydrology of a system, capturing stormwater volume through the use of soils, vegetation, and engineered systems that mimic nature. GI supports the principals of Low Impact Development (LID), an approach to land development or re-development that works with nature to manage stormwater close to its source. GI can be utilized at site-scale through practices such as green roofs, permeable pavement, and rain gardens; and at the watershed-scale through practices such as riparian buffers, flood plain preservation or restoration, and wetland creation or preservation.

Various regions of the U.S. have utilized GI for distinct primary goals. Cities in the Northeast, Midwest, and Pacific Northwest tend to implement GI as part of water quality compliance efforts, particularly those related to combined sewer overflows (CSOs). On the other hand, cities in water stricken areas of the U.S. tend to focus on GI for water reuse as well as stormwater discharge issues related to water quality.  In addition to these primary goals, many municipalities often consider the adoption of GI programs within a framework of sustainability goals that seek to maximize welfare gains for the respective communities, such as community revitalization, “green job” creation, and climate change mitigation and adaptation. Because gray infrastructure technologies do not seek to enhance the ecological resiliency of communities and are associated with high societal costs, integrating widespread use of GI into watershed focused planning represents a shift towards more sustainable environmental planning and stormwater management methods.

Many case studies have explored the barriers facing individual communities after stormwater management authorities have made the decision to adopt a GI program (Hammitt, 2010; Madden, 2010; U.S. EPA, 2010). Fewer studies have sought to bring together a more comprehensive view of common barriers to GI program adoption faced by multiple communities (Clean Water America Alliance, 2011; Roy et al., 2008). White and Boswell (2007) investigate the adoption of best practices for stormwater management across municipal governments in Kansas and find little difference in the quality of management responses across adopters. Several studies have also focused on the effects of select stages or processes on GI adoption, such as learning through communication channels (Dolowitz et al., 2012) and the perceptions of risk effect adoption decisions (Olorunkiya et al., 2012). A study by Carlet (2015) finds evidence that the perceived usefulness of the ecological and technical benefits of GI influences municipal planners’ and engineers’ attitudes toward adoption.

There is a need to develop a deeper understanding of why growing numbers of U.S. municipalities are considering the adoption of GI technologies, and to what degree these technologies are being used. Viewing the adoption of a comprehensive municipal GI program as a policy innovation, this paper investigates how social, environmental, and economic factors influence the decisions of CSO management authorities. Survey findings are incorporated into previous work that identified significant factors that influence municipal GI program adoption (Flynn and Davidson, 2016). The identified factors are used to investigate key differences affecting whether or not GI technologies are adopted by CSO management authorities in large U.S. cities, and the degree to which adopting authorities plan to implement GI technologies. This article is significant in several ways. First, as the article considers the adoption of an innovative infrastructure program for municipal governments, both the scale of the type of policy it considers are relatively underexamined in policy innovation studies. Second, the wide range of implementation plans associated with GI programs offers a unique opportunity to assess the intensive margin of adoption in a policy innovation, a measure that is less often assessed in policy innovation studies.

## 4.3 Background

### 4.3.1 Municipal Stormwater Management in the U.S.

Municipal policies to manage wet weather discharges in U.S. municipalities are designed around federal and state regulations which aim to improve urban water quality and prevent human health risks. Table 4.1 summarizes key legislative and regulatory action undertaken by the U.S. government in response to public concern regarding stormwater pollution. The Clean Water Act enacted a permit program, the National Pollutant Discharge Elimination System (NPDES), to manage and control point source discharges of pollution. Current regulatory and management approaches address municipal wet weather discharges under at least two distinct NPDES programs: stormwater management for municipal separate sewer systems, and wastewater management for CSOs, sanitary sewer overflows, and peak flow discharges at

**Table 4.1 Major U.S. legislative and regulatory actions related to municipal stormwater control (adapted from National Research Council, 2009)**

| **Government Actions** | **Enactment Date(s)** | **Summary and Implications** |
|---|---|---|
| Federal Water Pollution Control Act | 1948,<br>1952,<br>1955 | Provided federal financial assistance to state & local governments for wastewater treatment plans and state water pollution control programs |
| Water Quality Act | 1965 | Required federally approved state water quality standards and implementation plans |
| Federal Water Pollution Control Act<br>Clean Water Act Section 303(d)<br>Clean Water Act Section 208 | 1972 | • Prohibited discharge of pollutants into surface waters without a permit<br>• Outlines water-quality based strategies required if pollution remains after technology-based standards<br>• Designated and funded development of regional water quality management plans |
| Clean Water Act Sections 301 and 402 | 1977, 1987 | Regulated the release of toxic pollutants and established technology treatment standards for conventional pollutants and priority toxic pollutants |
| *NRDC vs. Costle* | 1977 | Stormwater discharges in the National Pollution Discharge Elimination System (NPDES) program |
| Clean Water Act Amended Sections 301 and 402 | 1987 | Required the management of urban stormwater pollution and stormwater permit programs for urban areas and industry |
| National CSO Control Strategy | 1989 | Encouraged states to develop NPDES permitting strategies for CSOs, and recommended six minimum CSO control measures |
| EPA's Phase I Stormwater Permit Rules | 1990 | Application and permit requirements for large and medium municipalities (≥ population of 100,000); light and heavy industrial facilities; and construction activity ≥ 5 acres |
| Combined Sewer Overflow Control Policy | 1994 | Assigns primary responsibility for CSO control implementation and enforcement to NPDES authorities and water quality standards authorities. Established objectives for CSO communities to 1) document and implement nine minimum controls measures, and 2) develop and implement a long-term control plan (LTCP) |
| EPA's Phase II Stormwater Permit Rules | 1999 | Permit requirements for all census-defined urbanized areas, and construction sites 1 to 5 acres |
| Total Maximum Daily Load (TMDL) Program Litigation | 1997-2001 | Courts order EPA to establish TMDLs in a number of states if the states fail to do so. Assigns Waste Load Allocations for stormwater discharges which must be incorporated as effluent limitations in permits |
| Wet Weather Water Quality Act | 2000 | CSO Control Policy endorsed in the Clean Water Act |

treatment facilities. In 1987, the U.S. Congress mandated that the U.S. Environmental Protection Agency (U.S. EPA) control certain stormwater discharges under NPDES, resulting in the Phase I Stormwater Rules (1990) and Phase II Stormwater Rule (1999) that set forth requirements for municipal separate storm sewer systems. The 1994 Combined Sewer Overflow Control Policy put in place a national approach to manage CSOs through the NPDES permit program, providing guidance for municipalities to implement CSO control measures in a flexible and cost-effective manner. Management plans produced by CSO management authorities are referred to as a Long-Term Control Plan (LTCP), which encompass several stages of analysis a CSO management authority must complete (e.g., characterization of a sewer system, defining control targets, and development and evaluation of alternative approaches to meet control targets).

There are notable distinctions between CSO control plans and municipal separate stormwater management plans. The Phase I rules required municipal separate stormwater system operators to develop a stormwater management program that reduces pollutant loadings and removes system pollutants to the "maximum extent practicable," which is left to be defined by each operator. Basic NPDES permit provisions for municipal separate stormwater systems are targeted at eliminating illicit discharges and controlling runoff from construction sites, redevelopment sites, and newly developed areas. These provisions can present large administrative burdens to municipal separate stormwater system operators, but generally do not require operators to fund large-scale capital infrastructure projects for wet weather control. Alternatively, for many cities with combined sewer systems, compliance with CSO control targets represent greater challenges to meeting water quality standards and require large financial investments to reach compliance. While federal and state funding assistance is available, local ratepayers ultimately fund the majority of CSO control projects. Thus, CSO control programs represent significant municipal investments that compete with other local programs. The financial requirements for the combined sewer system upgrades needed in U.S. communities to reach federal regulatory compliance was estimated at $48 billion in 2012 (U.S. EPA, 2016).

Municipal CSO LTCPs that were developed between 1994 and 2007 focused on gray infrastructure projects that reduce stormwater flows and enhance water quality through operation and maintenance practices, collection system controls, and storage facilities, and treatment facilities. While a 1995 EPA guidance document for LTCPs identified particular GI measures as potential source controls for wet weather (U.S. EPA, 1995), some municipal authorities faced barriers to using GI approaches for CSO compliance and instead adopted experimental or demonstration approaches for stormwater management (Siddique, 2009). During this time period, GI approaches were also commonly implemented as a form of injunctive relief in municipal Clean Water Act settlements. One example of an early GI program is the City of Portland's downspout disconnection program, which achieved about 4,400 disconnections per year from 1995 to 2006, removing approximately 1.5 billion gallons of stormwater per year from the combined sewer system (Portland Bureau of Environmental Services, 2010). The success of early demonstration projects led an influential 2006 report on the use of GI in various communities (Kloss et al., 2006), as well collaborative efforts between the EPA and national groups to promote GI as an environmentally preferable approach for stormwater management.

Since 2007, the US EPA's Office of Water has released several policy memos and other forms of support for authorized permitting authorities to structure their permits as well as guidance or criteria for stormwater plans and CSO LTCPs to utilize GI approaches. Table 4.2 summarizes some of various efforts of the EPA to encourage the use of GI to manage wet weather. While an increasing number of cities and states are integrating GI provisions into

**Table 4.2 Major U.S. EPA Office of Water policy memos, action strategies, and collaboration efforts related to green infrastructure**

| Document | Date | Summary and Implications |
|---|---|---|
| *Using Green Infrastructure to Protect Water Quality in Stormwater, CSO, Nonpoint Source and other Water Programs* | March 2007 | Promotes GI as a viable stormwater management solution across multiple EPA regulatory water programs. |
| *Green Infrastructure Statement of Intent* | April 2007 | Formalized collaborative effort between EPA and four national organizations to promote GI in stormwater control programs |
| *Use of Green Infrastructure in NPDES Permits and Enforcement* | August 2007 | Encourages incorporation of GI into NPDES stormwater permits and CSO LTCPs. Pledged that EPA could and would use GI in its future enforcement activities. |
| *Action Strategy for Managing Wet Weather with Green Infrastructure* | January 2008 | Identified objectives for the EPA and partner organizations to develop strategies to stimulate the use of GI throughout the US. |
| *Protecting Water Quality with Green Infrastructure in Water EPA Permitting and Enforcement Programs* | April 2011 | Reaffirms official commitment to work with communities to incorporate GI into stormwater permits and remedies for noncompliance |
| *Green Long Term Control Plan (LTCP) – EZ* | July 2011 | Template for CSO communities to assess GI as part of LTCPs |
| *Achieving Water Quality through Integrated Municipal Stormwater and Wastewater* | October 2011 | Encourages EPA Regions to assist their state and local partners in pursuing an integrated planning approach to Clean Water Act stormwater obligations. |
| *Integrated Municipal Stormwater and Wastewater Planning Approach Framework* | June 2012 | Framework for integrated planning to facilitate the use of sustainable and comprehensive solutions "that protect human health, improve water quality, manage stormwater as a resource, and support other economic benefits and quality of life attributes that enhance the vitality of communities." |
| *Federal Agency Support for the Green Infrastructure Collaborative* | July 2014 | Established partnership among seven federal agencies and outlines commitments of each agency in promoting GI |
| *Green Infrastructure Collaborative Statement of Intent* | October 2014 | Established network of 26 academic, nongovernmental, and private sector organizations committed to the advancement of GI in US communities |

municipal separate stormwater system permits, GI capital projects have been more commonly adopted by sewer management authorities in combined sewer system municipalities. CSO management authorities have sought multiple ways to adopt GI programs for CSO control, including the replacement of specific gray infrastructure projects in LTCPs with GI, public-private partnerships, and adaptive management programs that implement GI over time.

### 4.3.2 GI Program Adoption as a Policy Innovation

This study considers the adoption of a GI program for CSO management to be a policy innovation, as it represents a new program that guides infrastructure decisions for CSO management authorities. A policy innovation is generally defined as the adoption of a new policy or program by a government entity that had never utilized it previously (Walker, 1969). Numerous studies have sought to understand and explain why government agencies adopt particular policies or programs (Berry and Berry, 1990, 1999; Mintrom and Norman, 2009; Mintrom and Vergari, 1998; Walker, 1969). While most policy innovative research has focused on states as an adopter, an increasing amount of research has focused on the determinants of local policy innovation (Godwin and Schroedel, 2000; Shipan and Volden, 2006), including local environmental policy innovations (Krause, 2011; Pitt, 2010; Vasi, 2006; Wang, 2013; Zahran et al., 2008).

Traditional technology adoption models seek to measure the extensive margin of adoption, or a binary assessment of whether an innovation is adopted or not, and fail to capture the degree of intensity to which technologies are used once adopted (Comin and Mestieri, 2013). Alternatively, the intensive margin, or a measure of the intensity of the use of an innovation, is a key component in developing an understanding of its diffusion. GI programs for CSO management have a wide range of implementation plans, from hundreds of thousands of dollars for small-scale projects to billions of dollars for city-wide projects. While many policy innovations studies investigate only the extensive margin of a particular policy, this study investigates the intensive margin of adoption of GI program adoption, which can provide insight on the influential factors that distinguish “deep” and “superficial” commitments (Berry and Berry, 1999).

Common determinants of policy innovation include the political, economic, and social characteristics of a particular governance system. Local context has been shown to affect the likelihood of an innovation’s adoption, particularly regarding the local relevance and viability for the innovation, and the availability of local resources to accommodate adoption of the innovation (Ormrod, 1990). This study hypothesizes that a CSO management authority’s decisions related to GI program adoption are determined by the relative strengths of motivations and obstacles to environmental action, and by the resources available to overcome those obstacles.

## 4.4 Methods

### 4.4.1 Study Population

The population considered in this study includes U.S. CSO management authorities that provide combined sewer services for an urban population of at least 100,000 people[3]. A 2004 US EPA report lists 828 NPDES permits for authorized CSO discharges (U.S. EPA, 2004, p. Appendix D). These data were used to identify the CSO management authorities and associated combined sewer system municipalities. Each NPDES permit number was used to identify permittees (referred to here as the CSO management authorities, or simply “authorities”). The largest combined sewer system municipality managed by an authority was identified using

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[3] This population threshold was chosen in part due to the lack of planning documents available from authorities below this threshold.

NPDES permit information and CSO management authority websites. Data from the 2010 U.S. census were used to account for the population of each serviced municipality, resulting in 68 authorities identified as providing combined sewer management services for municipalities with populations of 100,000 or above. Documentation on the LTCPs for each community was collected through municipal websites and emails with municipal officials. Municipalities were removed from the study population if CSO compliance goals had been met before the year-end 2015 without the adoption of a GI program specifically for CSO compliance efforts. This process resulted in 53 CSO management authorities remaining in the study population. In cases when more than one CSO authority provides combined sewer services to a municipality, authorities are considered separately if each has a unique CSO compliance management plan.

### 4.4.2 Adoption Criteria

In reviewing the LTCPs of authorities in this population, GI approaches were often found to be adopted in two stages. First, a pilot program of GI demonstration projects is adopted to allow for authorities to directly monitor the effectiveness of various GI approaches. This is followed by a decision on whether a large-scale program is appropriate for CSO management goals. While many authorities report the adoption of demonstration projects, data on the timing and funding related to pilot programs were not consistently available across the study population. Thus, the GI programs considered in this study are only large-scale programs for CSO management. We define a large-scale program as one that dedicates at least one percent of overall planned capital expense funds to GI projects for CSO management. The present value of funding dedicated to an adopted GI program adjusted to 2010 dollars is used as an assessment of the intensive margin of GI program adoption. Alternative metrics for the intensive margin were considered, such as the estimated gallons of stormwater captured by planned GI projects relative to gray projects; however, these data were also not consistently available across all plans. For plans with funds allocated as flexible spending under the principle of adaptive management, we use 50% of the flexible spending value toward total GI funding. In cases when a funding range was given, the average value is used. The GI program is considered to be adopted once it is approved by a municipal government agency (e.g., a common council) or NPDES permitting authority. While many municipal governments may adopt GI programs that are not associated with the LTCPs of CSO management authorities, these are not considered within this study. Unapproved strategic plans recommended to or by a managing authority, and GI programs adopted as a form of injunction relief, are also not considered as a large-scale GI program adoption. In cases when multiple GI program updates were released by an authority before 2015, data on the earliest adoption of a large-scale GI program are used. Of the 53 CSO authorities in the study population, 22 were found to have adopted large-scale GI programs. Table A4.1 in Appendix A provides descriptions of the data sources for the adopted programs. Figure 4.1 shows the distribution of logged GI program funding amounts, adjusted to 2010 dollars. The natural log of GI funding is used to account for the positive skew of adopted GI program funding.

### 4.4.3 Independent Variable Selection

Independent variable selection builds on previous research that identified significant factors that influence municipal decisions related to GI adoption (Flynn and Davidson, 2016). Select variables from this study are categorized according to a social-ecological framework for municipal GI adoption. This framework organizes the internal determinants of a decision-making

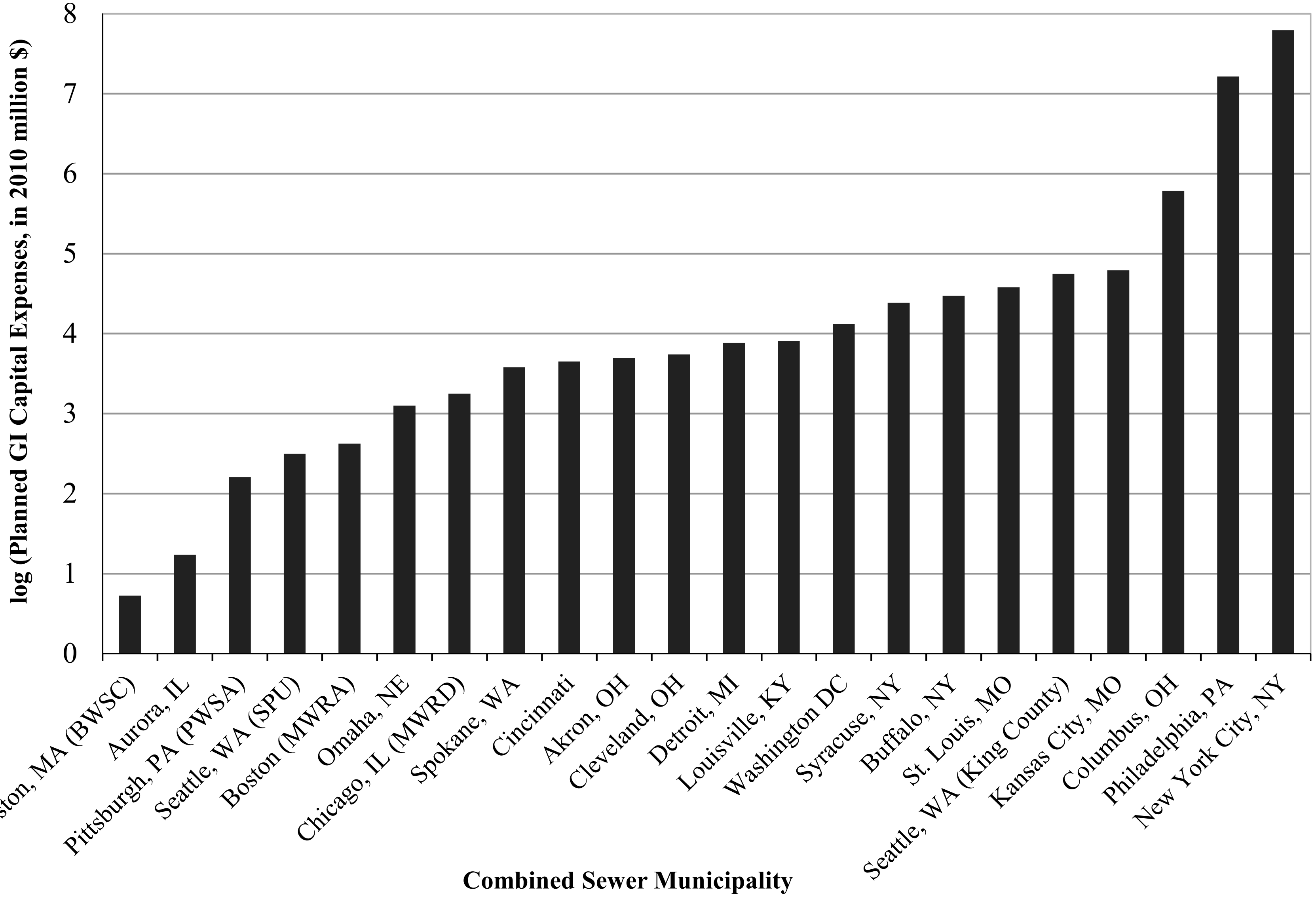

**Figure 4.1 Planned capital expenses for GI programs**

process into three categories: Resource System, Governance System, and Actors.

### *4.4.3.2 Resource System*

CSO control programs represent significant municipal investments that are required to meet Clean Water Act compliance goals. The communities considered in this study have a wide range of capital infrastructure needs for CSO abatement to meet these goals, as each community has implemented various stages of CSO management compliance efforts. The total funds needed for an authority to reach Clean Water Act compliance for CSO management are used as a control for the maximum potential infrastructure funding that a CSO authority is hypothesized to undertake.

A key measure of a stormwater management technology's effectiveness is the performance criteria to which the control is designed. A design storm is a typical approach to the sizing of stormwater control approaches. Design storms are defined by a recurrence interval designation (i.e., 1-year), indicating the probability that a storm of a certain size will occur during any given year, and a recurrence interval duration designation (i.e., 24-hour). Stormwater control measures such as GI approaches generally designed for smaller precipitation events (National Research Council, 2009). Thus, it is hypothesized that municipalities with smaller design storm sizes will be more likely to adopt a GI program.

### *4.4.3.2 Governance System*

CSO management authorities are tasked with making critical decision regarding financial resource allocations for capital infrastructure projects while under strict regulatory environments. Funding limitations are 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), most often in reference to the limited economic resources of enforcement organizations. As GI technologies are often viewed as less proven than traditional approaches, CSO management authorities may be less willing to allocate capital infrastructure funds to GI projects for compliance goals if the degree of effectiveness is uncertain, particularly if economic resources are scarce. Research on state policy adoption has found that larger states with greater economic resources are more likely to adopt policy innovations (Berry, 1994; McLendon et al., 2005; Walker, 1969). Furthermore, larger cities have been found to have higher rates of innovation (Bettencourt et al., 2007a; Hagerstrand, 1968), and to dedicate more administrative resources to planning initiatives (Burby and May, 1998). Accordingly, this study hypothesizes that larger and wealthier municipalities are more likely to have the resources necessary to adapt existing CSO management plans to include GI programs. Conversely, if GI programs are adopted as additional programs rather than a substitute for current infrastructure, interest in GI program adoption has to compete with other municipal priorities such as economic development and job growth. CSO management program funding guidance has commonly cited municipal unemployment rate as a primary measure of a municipality's ability to pay for CSO capital infrastructure projects. Thus, unemployment rate is used in this study as a competing factor that may hamper the incentive to adopt a large-scale GI program.

#### *4.4.3.3 Actors*

A survey was administered to municipal officials involved in GI planning efforts to collect additional data on factors that influence GI adoption. The survey included both open ended questions and questions with a five point Likert scale to collect both descriptive and quantitative data on each municipality. Administration took place during a 2014 national summit on GI that included delegates from US communities that had adopted or explored GI programs.

Surveys results for select questions from delegates representing 15 CSO management authorities in this study population are included Appendix A4.

Figure 4.2 shows the results for questions regarding the characterization of non-governmental organizations (NGOs) in GI planning efforts. The majority of delegates consistently agreed or strongly agreed that NGOs were successful in encouraging GI initiatives at a residential and governmental level, while in both a supportive and supervisory role. Open-ended questions allowed respondents to name the organizations that collaborated in GI adoption efforts. The most common types of NGOs listed were environmental organizations, particularly those related to water initiatives, and community development organizations. Interest group models of local policy adoption suggest that policy emerges from interest group competition, with the groups that effectively utilize political resources to lobby local elected officials being more likely to see their preferred policies adopted (Lubell et al., 2009). It is hypothesized that higher economic resources available to a municipality's nonprofit environmental organizations will increase the likelihood of GI program adoption.

The adoption of sustainable initiatives and policies in the US are often characterized by partisanship (Chandler, 2009; Guber, 2001). An independent variable indicating local political leanings is used to estimate the level of resident level support or opposition that may accompany the adoption of a GI program. It is hypothesized that a higher percentage of Democratic Party voters will lead to an increased likelihood of large-scale GI program adoption.

### 4.4.4 Data Description

Table 4.3 summarizes data sources used, while Table 4.4 provides summary statistics for each variable. For resource system factors, the average size of precipitation events is estimated

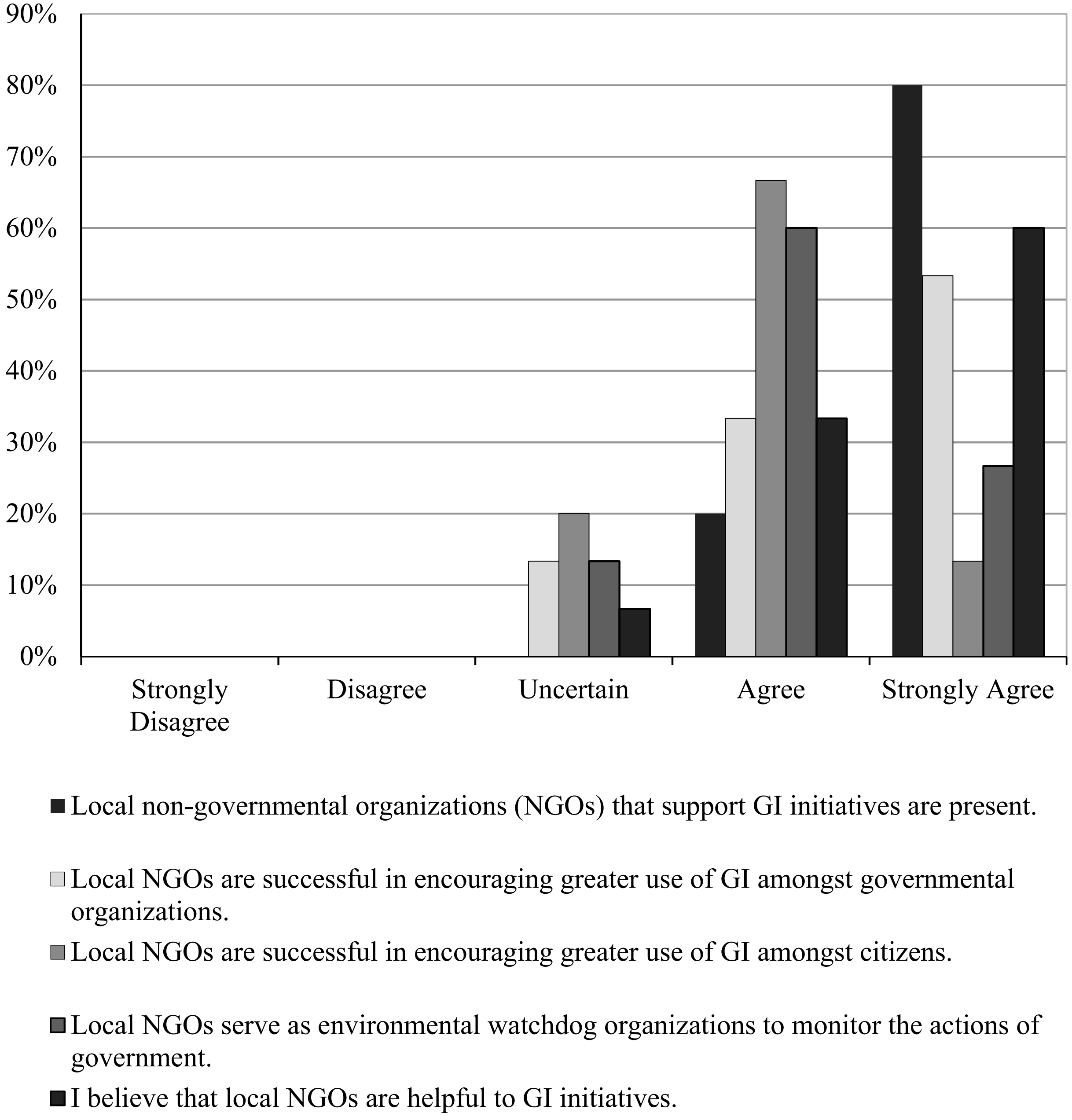

**Figure 4.2 Survey results on the involvement of NGOs in GI planning**

**Table 4.3 Variable description and data sources**

| Factors | Variable Measurement (Data Source) |
|---|---|
| **Resource System** | |
| **Average size of precipitation event** | 2-year 24-hour precipitation event size, inches<br>(NOAA Precipitation Frequency Data Server) |
| **Quality of built infrastructure** | Capital needs for CSO infrastructure to reach Clean Water Act goals<br>(2008 U.S. EPA Clean Watersheds Needs Survey) |
| **Governance System** | |
| **Population** | City population, 2010<br>(US Census) |
| **Economic resources** | Median household income, 2010<br>(American Communities Survey)<br>Unemployment rate, 2010<br>(American Communities Survey) |
| **Actors** | |
| **Socioeconomic attributes** | % Democratic Vote, 2008 #<br>(2008 Presidential Election, CQ Press) |
| **Environmental leadership** | Assets of registered environmental nonprofits, 2010 #<br>(National Center for Charitable Statistics) |

Notes: # indicates County level data. Per capita values for data collected at the County level are normalized using County population values collected from the 2010 US Census. For municipalities with multiple counties, a weighted average based on the population of each county that resides in municipality is used.

**Table 4.4 Summary statistics**

| | Full Population (N=53) | | | | GI Adopting Population (N=22) | | | |
|---|---|---|---|---|---|---|---|---|
| **Variable** | **Mean** | **Std. Dev** | **Min** | **Max** | **Mean** | **Std. Dev** | **Min** | **Max** |
| **2-year 24-hour precipitation event size, inches** | 2.94 | 0.48 | 1.50 | 3.67 | 2.75 | 0.47 | 2.07 | 3.55 |
| **log(CSO capital infrastructure needs, dollars per person)** | 6.99 | 1.47 | 1.72 | 8.99 | 7.12 | 1.34 | 2.45 | 8.70 |
| **log(City population)** | 12.5 | 0.89 | 11.52 | 15.9 | 13.2 | 0.92 | 11.9 | 15.9 |
| **Median household income, thousand $** | 44.7 | 12.1 | 27.4 | 88.0 | 45.2 | 14.9 | 27.4 | 88.0 |
| **Unemployment rate, %** | 6.77 | 1.90 | 3.00 | 13.50 | 7.01 | 2.22 | 4.50 | 13.5 |
| **Democratic vote, %** | 62.4 | 11.4 | 37.0 | 93.4 | 67.3 | 12.0 | 49.4 | 93.4 |
| **log(Assets of Environmental NGOs, dollars per person)** | 3.86 | 1.63 | 0 | 8.44 | 4.44 | 1.58 | 1.36 | 8.44 |
| **log(Planned GI funding, adjusted to 2010 dollars)** | - | - | - | - | 3.91 | 1.65 | 0.72 | 7.79 |

using a 2-year, 24-hour precipitation frequency from the National Oceanic and Atmospheric Administration Precipitation Frequency Data Server. The quality of an authority's sewer infrastructure is determined using the capital funding needs for CSO infrastructure to reach Clean Water Act goals from the 2008 Clean Watersheds Needs Survey (U.S. EPA, 2012), normalized on a per capita basis. Unemployment rate and median household income fare collected from the American Communities Survey. Percentage of Democratic Party voters are measured using the percent total Democratic votes in the 2008 Presidential Election as reported by CQ Press (CQ Press, 2017). Data from the National Center for Charitable Statistics (NCCS, 2016) are used for environmental leadership, measured using the annual assets of registered environmental nonprofits. Population data are collected from the 2010 U.S. Census.

### 4.4.5 Model Specifications

To empirically examine the influence of factors on the extensive and intensive margins of adopting a comprehensive GI program, a lognormal hurdle model is used. Hurdle models were first proposed by Cragg (1971) to allow for two sets of explanatory variables in the determination of purchasing behaviors. This approach allows for the non-adoption of a large-scale GI program to be treated as a corner solution (as opposed to unobserved) and for the program adoption and funding decisions to be determined by separate combinations of factors.

The lognormal hurdle model (Wooldridge, 2010) is characterized as

$$y_i = s_i\, y_i^* = 1[\,\gamma z_i + u_i\ > 0]\exp(\beta x_i + v_i) \tag{1}$$

where $y_i$ is the observed value of GI program funding, $s_i$ is the binary selection variable for adoption, and $y_i^*$ is the latent variable representing GI program adoption, $z_i$ is a vector of explanatory variables describing the adoption selection, $\gamma$ is a vector of coefficients, $\epsilon_i$ is a standard normal error term, $x_i$is a set of explanatory variables describing the program funding amount, $\beta$is a vector of coefficients, and $u_i$ and $v_i$ are independent, homoscedastic, normally distributed error terms. The selection equation is governed by a probit model. Vectors $z_i$and $x_i$ are kept identical to assess the effects of each variable in the two decision stages. The model is estimated using maximum likelihood techniques in *Stata* with the log likelihood as follows:

$$l_i = 1[y_i = 0] \log[1 - \Phi\,(\gamma z_i')] + 1[y_i > 0] \log[\Phi\,(\gamma z_i')] \tag{2}$$
$$+1[y_i > 0] \left\{ \log \left\{ \phi \left[ \log(y_i) - \frac{\beta x_i'}{\sigma} \right] \right\} - \log(\sigma) - \log(y_i) \right\}$$

To relax the assumption homoscedasticity of $v_i$, heteroskedastic conditional variance is modeled as

$$\sigma^2(w_i) = \exp(2 w_i' \theta) \tag{3}$$

where $w_i'$ is a set of exogenous variables, and $\theta$ is the parameter vector. In this study, $w_i'$ is hypothesized to vary with municipal population, as factors that are not explicitly defined in the model likely have population scaling effects (Bettencourt et al., 2007b, 2007a).

## 4.5 Results

Table 4.5 presents the regression results of GI program adoption for equation (1) and average marginal effects of the selection probability and conditional GI program funding amounts with respect to all independent variables. Table A4.2 in Appendix A4 presents the regression results for the same model fitted to the outcome variable of planned gray infrastructure expenses for GI program adopting communities. The results in Tables 4.5 and A4.2 indicate that the extent of both GI spending and gray infrastructure spending are strongly driven by remaining funding required for CSO compliance goals and municipal population. These variables are considered as controls in assessing the extent of any type of CSO

## Table 4.5 Hurdle model of GI adoption for CSO management

| | **Selection of GI Program** | | **Amount of GI Funding** | |
|---|---|---|---|---|
| **Variable** | **(1)** | **(2)** | **(1)** | **(2)** |
| 2-year 24-hour precipitation event size, inches | -1.635**<br>(0.676) | -1.985**<br>(0.683) | -0.379***<br>(0.148) | -0.995***<br>(0.341) |
| log(Capital needs for CSO infrastructure, dollars per person) | 0.361*<br>(0.225) | 0.592**<br>(0.246) | 0.242***<br>(0.051) | 0.629***<br>(0.134) |
| log(City population, thousand people) | 1.636***<br>(0468) | 1.967***<br>(0.521) | 0.368***<br>(0.073) | 0.934***<br>(0.158) |
| Median household income, thousand $ | 0.007<br>(0.036) | -0.012<br>(0.036) | -0.019***<br>(0.006) | -0.049***<br>(0.015) |
| Unemployment rate, % | -0.144<br>(0.216) | -0.274<br>(0.216) | -0.136***<br>(0.035) | -0.352***<br>(0.090) |
| Democratic vote, % | 0.021<br>(0.032) | 0.038<br>(0.033) | 0.018**<br>(0.008) | 0.046**<br>(0.020) |
| log(Assets of environmental NGOs, dollars per person) | 0.106<br>(0.192) | 0.013<br>(0.195) | -0.095**<br>(0.045) | -0.250**<br>(0.122) |
| constant | -19.528***<br>(6.280) | | -3.238***<br>(0.099) | |
| log(σ) log(City population, thousand people) | | | -0.102***<br>(0.012) | |
| N | 53 | | | |
| Log likelihood | -17.670 | | | |
| AIC | 69.340 | | | |

Note: GI funding levels are logged values in million dollars adjusted to 2010 price. Columns 1 and 3 report coefficient estimates from maximum likelihood, and column 2 and 4 report the corresponding average marginal effect. Standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

management fund planning. The heteroskedasticity of the error term modeled with the natural logarithm of municipal population was found to be significant for both the conditional GI program funding level and conditional gray infrastructure funding level.

Precipitation event size characteristics are found to be strongly significant in both the selection and amount decision levels for GI program adoption. This supports the hypothesis that municipalities experiencing large precipitation events more frequently relative to the other CSO communities in this population are less likely to adopt GI for CSO management, and tend to dedicate less overall funding toward a GI program when a program is adopted. A growing body of research has demonstrated the effectiveness of GI approaches during large events (Horst et al., 2010; Lewellyn et al., 2015). This suggests that authorities may be unaware of the effectiveness of GI approaches for larger storm events, or that perceptions of GI limitations may have a greater influence on GI adoption decisions than research supporting the effectiveness of GI technologies. However, it should be noted that storm size characteristics are associated with climatic regions of the U.S., suggesting that the influence of this factor may include regional variation characteristics not captured in this model.

In terms of governance resource factors, median household income and unemployment rate were found to be strongly significant in the GI funding amount decision level but not the program selection decision level. The strong negative effect of unemployment rate supports the hypothesis that GI programs may be competing for other municipal program and development funding, as a higher rate of municipal unemployment results in less GI program funding adopted. Interestingly, median household income is also shown to have a significant negative relationship with the amount of GI program funding. One possible explanation for this relationship is that authorities that adopt large-scale GI programs do so in part for community redevelopment purposes. The relationship between higher amounts of GI funding with lower median household incomes may suggest that some authorities adopt a greater extent of GI technologies that provide additional public services in municipal populations that are experiencing a greater relative level of fiscal stress.

The coefficient on the voting preference influence is positive and moderately statistically significant at the program amount decision, indicating an increased amount of GI funding adopted in cities with a higher percentage of residents with Democratic voting preferences. This corresponds with research on ideological preferences for sustainability policies (Chandler, 2009; Guber, 2001). The coefficient for local environmental NGO support is negative in both the selection and amount models, and moderately significant at the amount model level, which indicates a higher per capita level of environmental NGO assets is associated with lower levels of GI program funding. One possible explanation for this unexpected result is that communities with lower levels of environmental NGO assets are able to effectively do “more with less” through campaigning for their policy interests without the need for monetary funding. Another reason may be that there are higher levels of per capita environmental NGO assets in communities where public authorities take less action for sustainability initiatives such as GI programs, and residents have effectively built more capital to fill the need for local environmental initiatives. Alternative functional forms for this variable were tested, such as the number of environmental NGOs per capita or using metrics for environmental NGOs categorized as water-initiative based organizations, and the overall model results and marginal effects were similar in each case. In comparing these findings with those from the survey results, the regression results suggest that the metrics used in this study are not able to fully capture the strength of interactions of individual organizations in their lobbying efforts for GI programs.

Two authorities' GI program amounts were identified as outliers, with values over two standard deviations above the mean. These data points were removed from the population, and the remaining population was used to re-analyze the fit of the model presented in Table 4.5. Table A4.3 in Appendix A4 shows the results for GI program adoption with outliers removed. Overall, the coefficients and average marginal effects for most independent variables in both the selection model and amount model remain relatively consistent. The sensitivity of municipal population size is tested using County level population data, collected from the 2010 US Census. These results are included in Table A4.4 in Appendix A4. The models display little variation in the significance or effect sizes across all independent variables for both the selection and funding amount models.

## 4.6 Discussion and Conclusions

Over the past decade, GI programs have transformed from site-scale demonstration projects to city-wide initiatives that seek to reduce the negative social and ecological impact of highly impervious urban environments. This study provides the first comprehensive, quantitative assessment of factors influencing stormwater management authorities' decisions related to GI program adoption. Overall, we find that the decision to adopt a large-scale GI program is strongly driven by the population size and precipitation event characteristics of a municipality, while the extent of program adoption is additionally driven by municipal socioeconomic characteristics, including residents' political preferences, median household income, and unemployment rate.

Assessing CSO management authorities' decisions related to GI program adoption provides a first step to understanding sustainable design decisions related to municipal stormwater management systems. Two limitations of this study that can guides future research should be noted. First, the GI programs analyzed are the initial GI program plans adopted by CSO management authorities. Initial program plans only capture preliminary commitments and goals for implementation. Some authorities may choose to commit additional funds over time, while authorities that do not have legal stipulations for specific plans or funding amounts may choose to implement less GI than original commitment levels. Thus, the findings on the extent of GI plan adoption reflect a particular willingness and ability to adopt a degree of GI at the start of a program. How GI technologies are implemented over time by CSO management authorities and other stormwater management authorities deserves additional research in the future.

Second, this study focuses only on GI capital projects by CSO management authorities for CSO compliance. Thus, it does not give a full picture of GI adoption in municipalities. Many municipalities adopt substitutes for the capital improvement GI programs adopted by CSO managing authorities. For instance, GI policies are commonly adopted within municipal stormwater management ordinances to require or encourage low impact development practices on new and redevelopment sites. Capital programs such as those for CSO management are also commonly adopted in other municipal departments, such as parks and recreation or transportation departments. Finally, GI may be adopted by CSO management authorities after Clean Water Act compliance goals have already been reached. Examining the diffusion of policy substitutes for GI capital improvement programs would provide a more complete picture of how and why municipal authorities choose to adopt GI policies.

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## Appendix A4

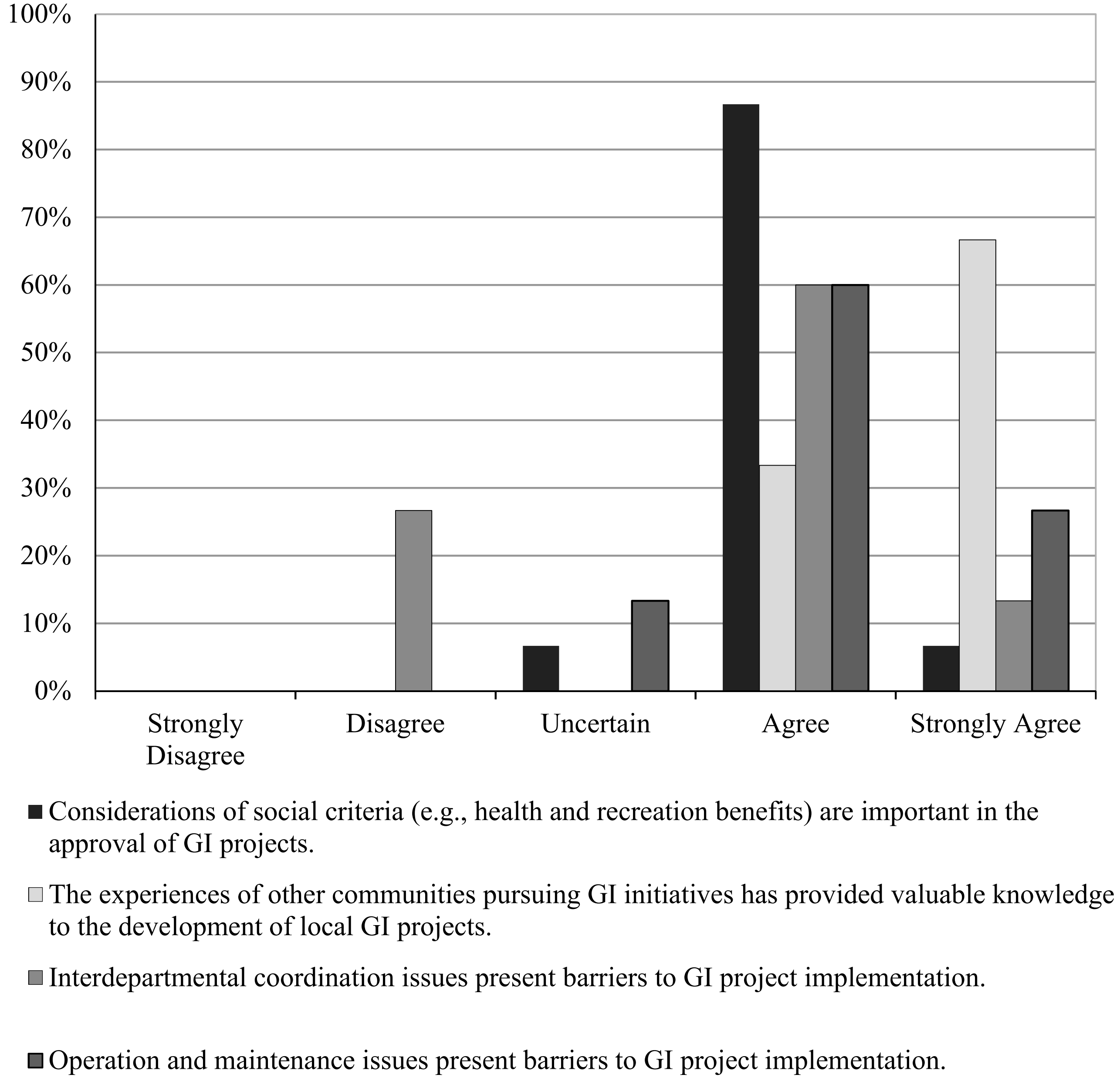

**Figure A4.1 Survey results on the adoption and implementation of GI plans**

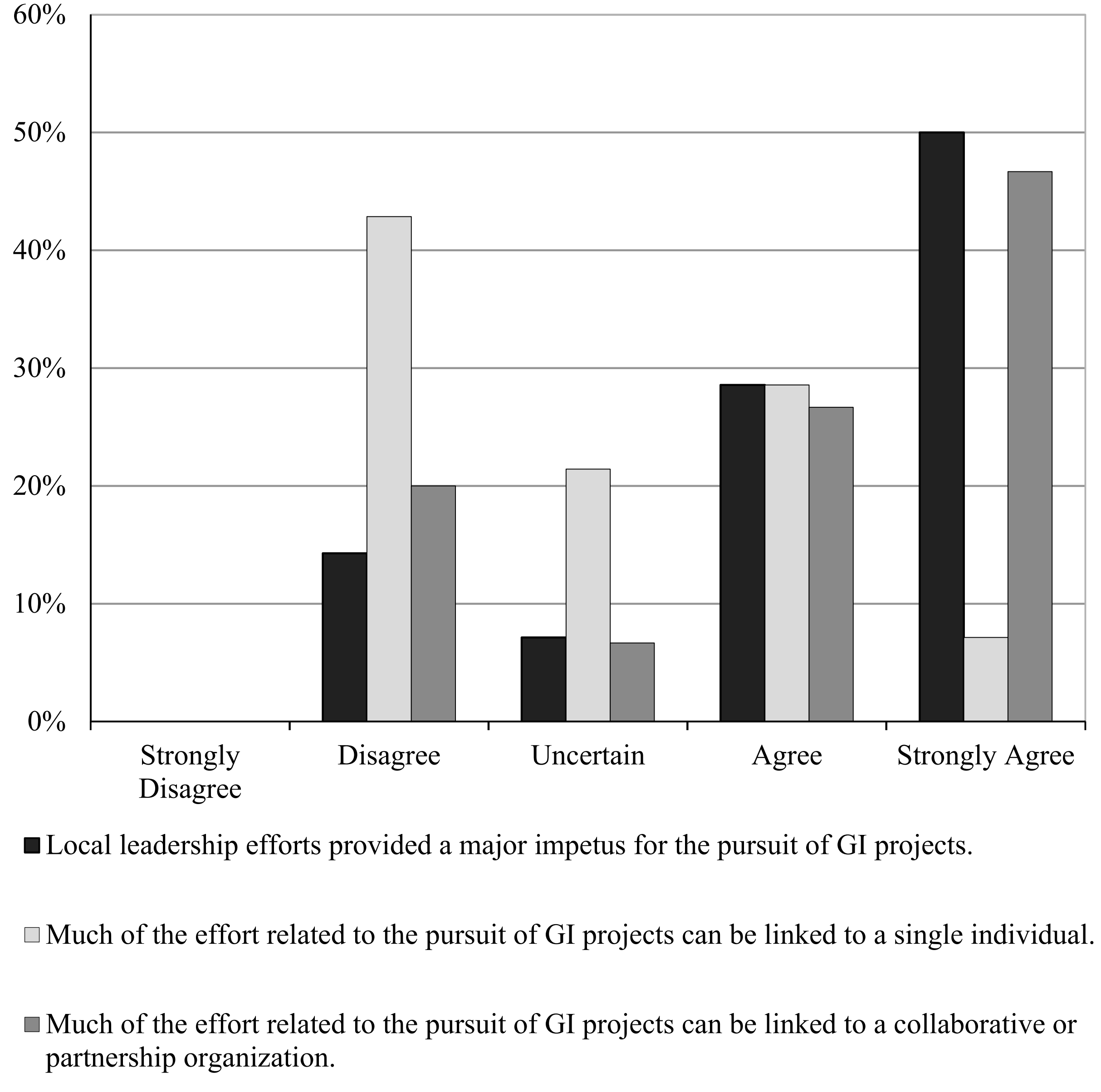

**Figure A4.2 Survey results on the role of leadership in GI planning**

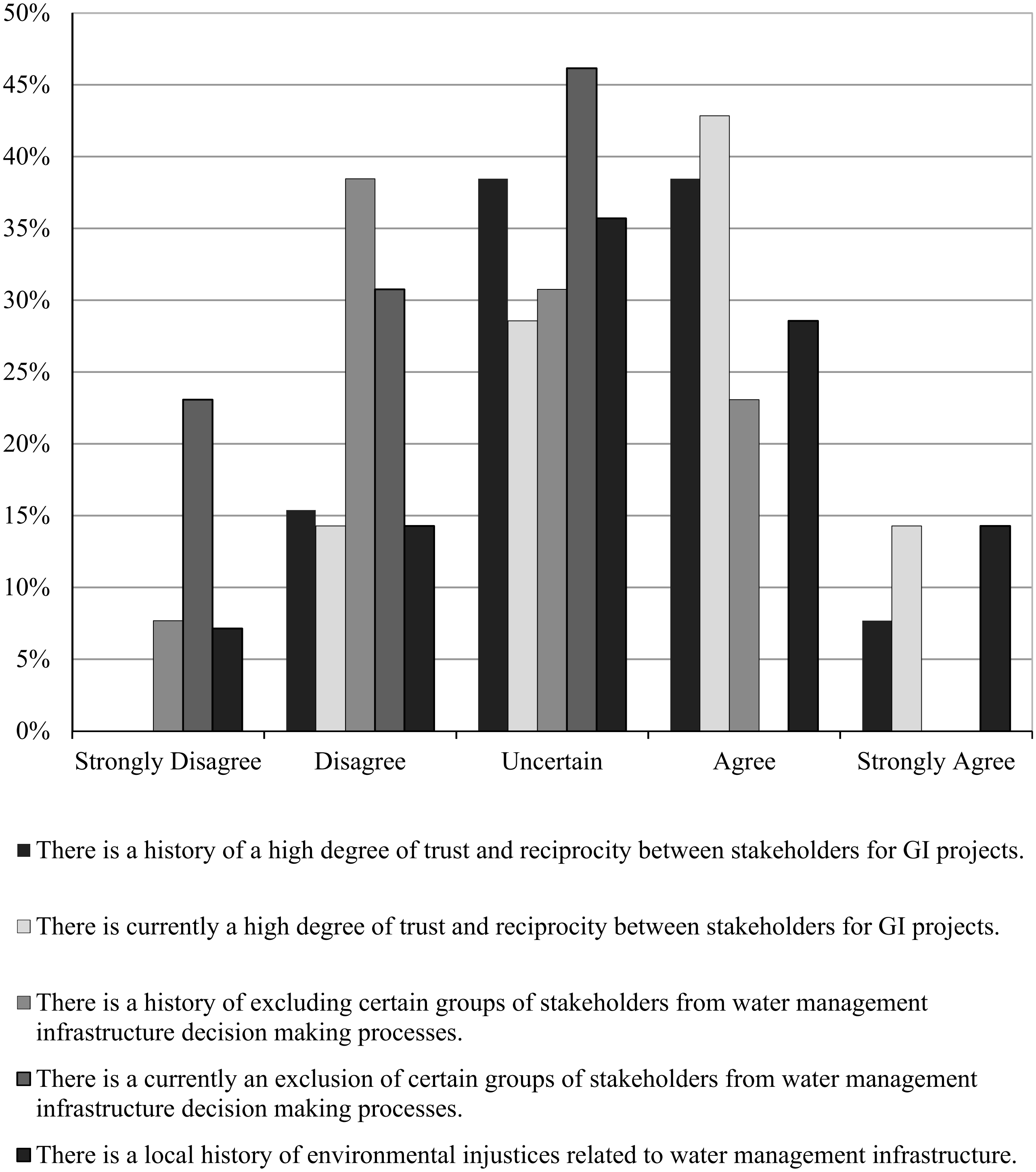

**Figure A4.3 Survey results on the characterization of stakeholder interactions in GI planning**

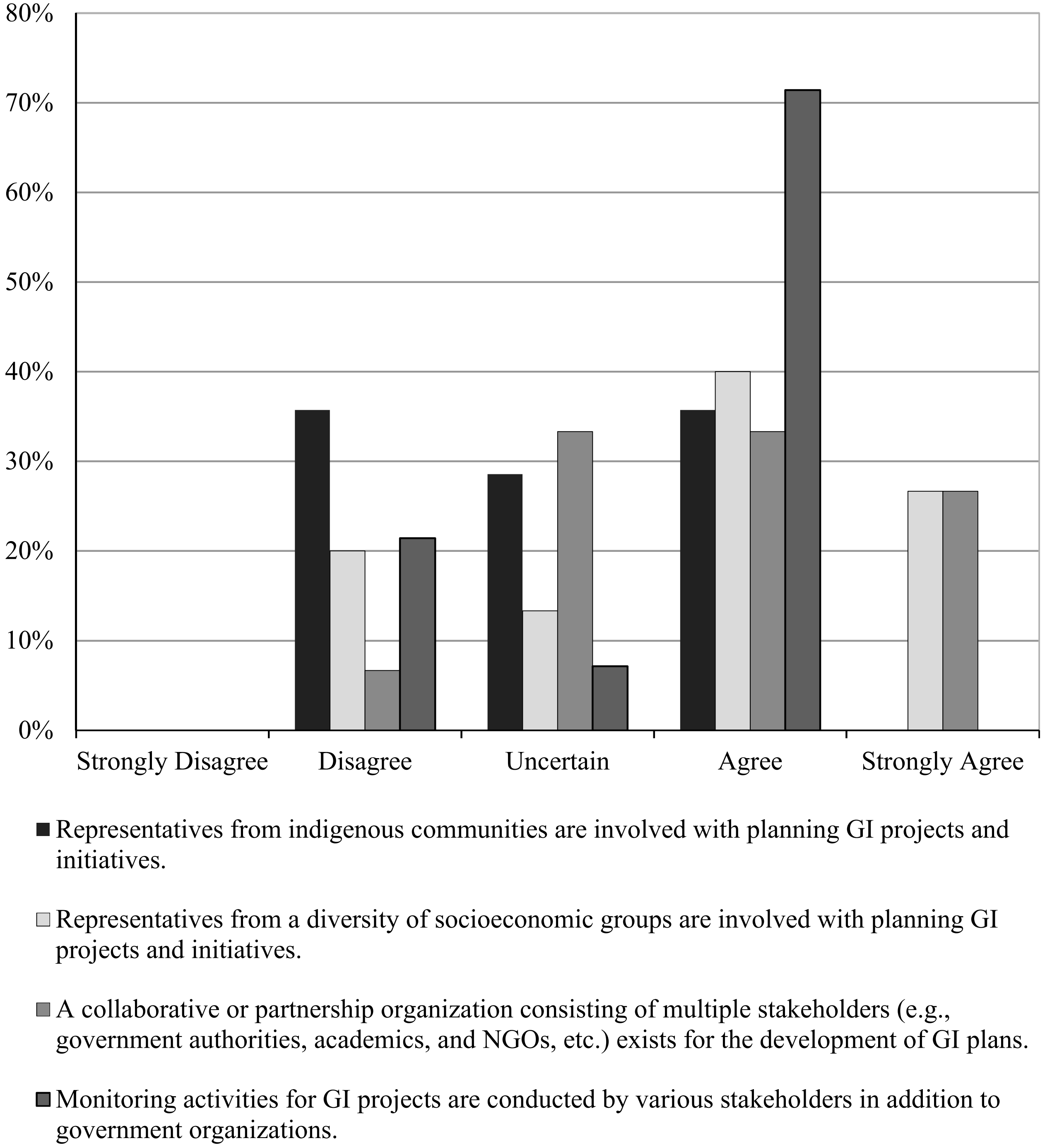

**Figure A4.4 Survey results on involvement of various groups in GI planning**

## Table A4.1 Descriptions of adopted GI programs

| **Authority Name** | **Combined Sewer City Managed** | **Total Planned Capital Funding for GI** | **Notes and source used for funding amount** |
|---|---|---|---|
| **City of Akron** | Akron, OH | 46 | On November 13, 2009, the City of Akron agreed to a consent decree for CSO compliance. This agreement and a 2011 LTCP update allows for green for gray replacement of previous plans. The City of Akron submitted an Integrated Plan to the EPA in August of 2015. The overall program is referred to as “Akron Waterways Renewed!”. Three green projects from the Integrated Plan were approved in December 2015, totaling $46 million in planned costs. |
| **City of Aurora, IL** | Aurora, IL | 3.44 | The City of Aurora and Fox Metro Water Reclamation Plant collaborate on the investigation, maintenance and repair of combined and separated sewers throughout the City of Aurora. The City of Aurora’s LTCP (dated March 2010, revised April 25, 2011, approved July 31, 2014) includes several GI projects (2010 LTCPU, Table 5.02-01) |
| **Massachusetts Water Resources Authority (MWRA)** | Boston, MA | 13.8 | One LTCP is shared by MWRA and the City of Cambridge. MWRA’s final CSO LTCP was approved in 1998 and revised in 2006. The total cost of the CSO control program is $857 million (FY12 CIP). The revised CSO control plan for the Alewife Brook comprises several component projects that were individually incorporated into the Court Schedule in April 2006. In 1997, MWRA originally agreed to $13.8 million for a wetlands project in the court schedule (out of $487 million when EPA and DEP approved the Final CSO Facilities Plan and Environmental Impact Report in 1997). Sources: MWRA 2004 Annual LTCP progress report, page 13 MWRA 2013 Annual LTCP progress report |
| **Boston Water and Sewer Commission (BWSC)** | Boston, MA | 2.24 | A consent decree was signed in 2012 requiring BWSC to initiate GI demonstration projects and to control pollutants other than sewage, using GI best practices to manage these pollutants wherever possible. Source: BWSC 2014-2016 Capital Improvement Program (2013), Table 15 |

| | | | |
|---|---|---|---|
| **Buffalo Sewer Authority (BSA)** | Buffalo, NY | 92.61 | On April 30, 2012 BSA submitted a LTCP, which has since been revised and was submitted on January 10, 2014. On April 14, 2014, the plan including GI was approved by the Environmental Protection Agency and the New York State Department of Environmental Conservation. Source: BSA 2014 LTCP, Table ES-6 |
| **Metropolitan Water Reclamation District of Greater Chicago (MWRD)** | Chicago, IL | 37.5 | 1972 began the Tunnel and Reservoir Plan (TARP) for flood control and pollution prevention. In 1995, TARP was approved as the LTCP for MWRDGC, Chicago, and 40 satellite communities. In 2011, MWRD entered a consent decree for CSO violations (was delayed until 2014 approval). The consent decree contains a requirement that MWRD spend $25-50 million to develop 10 million gallons in retention capacity using GI by 2015 Source: 2014 consent decree requires $25-50 million dollars be spent on GI. / Note: The City of Chicago has several GI programs (e.g., green roof and green alley programs) embedded in a number of departments, including $50M GI strategy released in 2014. However, the City does not have separate consent decree or LTCP. |
| **Metropolitan Sewer District (MSD)** | Cincinnati, OH | 34.41 | Consent Decree was entered in 2006 for a global wet weather plan. Final Wet Weather Improvement Plan approved in federal court in 2010 that focuses on CSO control and implementation of SSO correction plan. MSD has a three-prong approach – storage and conveyance, product control, and source control to control sources of overflows (includes GI). Cost: Capped at $1.5 billion over a period of 19 years. Source: 2010 Wet Weather Improvement Plan, Attachments 1B and 4 (Attachment 4 items includes: Green Program, Regional BMPs, and Long Term Projects) |
| **Northeast Ohio Regional Sewer District (NEORSD)** | Cleveland, OH | 42 | Original plan approved in 2003. Revised 2010 plan includes combination of gray infrastructure and GI at a cost of $3 billion over 25 years. NEORSD signed a Consent Decree in July 2011 which replaced a LCTP submitted in 2003. Source: Appendix 3 of 2010 Consent Decree (signed 2010, filed 7/7/11) |
| **City of Columbus, Department of Public Utilities** | Columbus, OH | 373 | LTCP and Wet Weather Management Plan (WWMP) submitted in 2005 and approved in 2009, estimated to cost $2.5B over 20 years. In 2012, Columbus's "Blueprint Columbus" plan was proposed (and officially accepted in 2015) as a replacement to the 2005 WWMP. Blueprint plan is projected to cost a total of about $1.78B and GI is $373M Source: 2015 Columbus Blueprint, p 153, approved by the Ohio EPA on December 1, 2015 |

| | | | |
|---|---|---|---|
| **Detroit Water and Sewerage Department (DWSD)** | Detroit, MI | 50 | Detroit adopted a LTCP in 1993 with a $2.2 billion CSO program. The primary aspect of Detroit's plan, the Upper Rouge Tunnel (est. to cost $1.5 billion) was cancelled in 2009 due to financial hardship that exceeded EPA's criteria. Detroit's Alternative Rouge River Control Plan includes 25 phased projects focusing on GI (to reduce CSO volume by 10-20%). Source: 2011 Alternative Rouge River Control Plan |
| **Kansas City's Water Services** | Kansas City, MO | 114 | Kansas City submitted an Overflow Control Plan in 2008, including a GI program. If pilots are successful, additional gray infrastructure projects may be replaced with GI. Overall cost is approximately $2.5 billion control plan over 25 years Source: 2009 Overflow Control Program, Table 12-20 / Note: Total of programmatic elements plus Combined Sewer System Items. GI items are all programmatic elements minus Blue River Watershed Management Plan, GI pilots, and Distributes Storage for Outfalls 059 and 069. Approved by the MDNR by letter dated April 14, 2010 |
| **Louisville and Jefferson County Metropolitan Sewer District (MSD)** | Louisville, KY | 47 | Louisville and Jefferson County MSD entered a 2005 Consent Decree, which was amended in 2009. Approved Plan (2009) includes $47M to GI. An Integrated Overflow Abatement Plan (IOAP) will be constructed over next 13 years at cost of $850 million and will address both combined systems as well as sewer systems with overflows. Source: Integrated Overflow Abatement Plan, Final CSO LTCP Volume 2 of 3 / MSD received a conditional letter of approval from the regulatory agencies on October 23, 2009. |
| **The City of Omaha** | Omaha, NE | 24.76 | First LTCP was submitted to Nebraska Department of Environmental Policy (NDEQ) in September 2009, and was approved by NDEQ in February 2010. The 2009 cost estimate was $1.66B (2009$) with 15-year schedule. 2014 LTCPU includes improvements to the WTP, added facilities, deep tunnel, 2 retention treatment basins, 2 storage tanks, and GI plan. Source: 2014 LTCPU, approved by NDEQ in January 2015 |
| **New York City Department of Environmental Protection** | New York City, NY | 2426 | In 2007, PlanNYC formed inter-agency task force and released a Sustainable Stormwater Management Plane in 2008. In 2010, NYDEP released Green Infrastructure Plan, which extends on 2008 plan and provides details on CSO management through GI. 2011 consent decree amendment states that LTCPs will incorporate elements of plan to achieve 10% city-wide application rate by 2030. Source: 2011 consent decree (March 13, 2012 - The New York State DEC and New York City DEP announced an agreement on 2011 enforcement order) |

|  |  |  |  |
|---|---|---|---|
| **The Philadelphia Water Department (PWD)** | Philadelphia, PA | 1323 | LTCP update submitted in 2009 (Green City, Clean Waters). A 2011 consent order approved amended plans from 2009. The revised plan includes cumulative spending of $345M for gray, $1670M for GI, and $420 million for adaptive funds. The LTCP includes large scale implementation of GI within a 25-year period that emphasizes the economic and social benefits Source: LTCPU (*Green City Clean Waters*, amended 2011, p 20), approved by Philadelphia Department of Environmental Protection in 2011, approved by EPA on 4/10/12. Note: green funds used here include 50% of planned flexible funds |
| **Pittsburgh Water and Sewer Authority (PWSA)** | Pittsburgh, PA | 9.86 | A Wet Weather Feasibility Study was submitted in 2013 to fulfill the requirements of the City of Pittsburgh/PWSA consent order agreement. PWSA proposed an evaluation of the ability of GI and integrated watershed management (IWM) to assist in the control of combined sewer overflows as the first step of a broader adaptive management plan aimed at optimizing the recommended approach to meeting legal requirements. Source: Table ES-2 in 2013 Wet Weather Plan |
| **King County** | Seattle, WA | 115 | In April of 2008, the County completed the 2008 CSO Control Plan Update, summarizing the County's progress on its CSO projects and the effectiveness of the projects it had undertaken (this report mentions LID but no active or planned LID projects). EPA issued Seattle and King County a Consent Order in 2009 to increase efforts to reduce CSOs. King County's 2012 proposed plan has cost of $711 million with $115 toward GI. Source: 2012 CSO control plan amendment p 5-41 (adopted in 2012, approved in 2013). Total plan cost is $711, GI life cycle planning costs are assumed to replace gray costs 100% |
| **City of Seattle, Seattle Public Utilities (SPU)** | Seattle, WA | 12.16 | The 2001 CSO Reduction Plan Amendment reevaluated previously studied areas of the City and expanded the evaluation to include other areas. The 2005 Update was prepared to evaluate the effectiveness of best management practice (BMP) projects from the 2001 Amendment that had been completed, and to revise cost estimates and schedules for remaining 2001 projects. 2010 CSO Plan update incorporate extensive GI strategies as part of the toolbox to meet goals. Source: 2010 CSO Plan update / Note: 2015 Approved Plan: Seattle's CSO control plan continues to use a combination of the following CSO control strategies: sewer system upgrades; natural drainage solutions – measures such as rain gardens, porous pavement, and cisterns that use soil to absorb stormwater); and underground storage, that would be jointly built by King County and Seattle. |

|  |  |  |  |
|---|---|---|---|
| **City of Spokane** | Spokane, WA | 40 | 2005 plan estimated to cost $314M; 2013 update: $183M; 2014 integrated plan: determined that implementing GI solely for the purpose of CSO reduction is not cost-effective when compared with storage and conveyance facilities, but GI will be implemented jointly with other infrastructure improvements, GI projects listed at a total capital cost of $40M, On May 5, 2014, the Spokane City Council passed a resolution, adopting the City's Integrated Clean Water Plan. A final draft of the plan was completed in December 2014. Source: 2013 Spokane Integrated plan |
| **Metropolitan St. Louis Sewer District (MSD)** | St. Louis, MO | 100 | 2011 Consent Decree and Approved Plan: Ongoing system improvements as well as new components, including GI. Total plan is $ 1.8 billion for CSO control plan, including $100 million for enhanced GI. 25-year baseline schedule for implementing CSO controls with substantial rate increases. Source: 2011 Consent Decree (approved 8/4/2011) and associated LTCP (capital costs in Table ES-2, also present PV) |
| **Onondaga County** | Syracuse, NY | 83 | GI program adopted with 2009 amended consent judgement. Revised plans replaced several large gray infrastructure projects, including a regional treatment facility. Cumulative GI costs estimated at $83M Source: GI Program report (Onondaga County, New York Save the Rain Program 2010-2018 Green Infrastructure Plan, page 7) |
| **District of Columbia Water and Sewer Authority (D.C. Water/WASA)** | Washington DC | 90 | The LTCP was developed in 2002 and approved in 2004, included $3M in LID demonstration projects on WASA projects (out of $1262B, ~0.2% overall spending). Pages 9-4 and 9-5 point out barriers to extensive LID). The LTCP was estimated to cost $1.3 billion. 2015 LTCPU (Clean Rivers Project) - On May 20, 2015, the EPA, the Department of Justice, DC Water and the District of Columbia agreed to the Consent Decree Modifications included in the revised agreement that will cost $2.6 billion and take 15 years to complete.GI Projects: $60 million for GI in Rock Creek and $30 million for GI for the Potomac CSOs 027, 028 and 029. |

**Table A4.2 Hurdle model of gray infrastructure expenses for GI program adopting communities**

| | Selection of GI Program | | Amount of Gray Infrastructure Funding | |
|---|---|---|---|---|
| **Variable** | **(1)** | **(2)** | **(3)** | **(4)** |
| 2-year 24-hour precipitation event size, inches | -1.635** | -3.528*** | -0.083 | -0.450 |
| | (0.676) | (1.374) | (0.074) | (0.389) |
| log(Capital needs for CSO infrastructure, dollars per person) | 0.361* | 1.149** | 0.201*** | 1.087*** |
| | (0.225) | (0.490) | (0.025) | (0.135) |
| log(City population, thousand people) | 1.636*** | 3.688*** | 0.163*** | 0.869*** |
| | (0468) | (1.012) | (0.033) | (0.163) |
| Median household income, thousand $ | 0.007 | 0.022 | 0.004 | 0.022 |
| | (0.036) | (0.074) | (0.002) | (0.016) |
| Unemployment rate, % | -0.144 | -0.299 | -0.002 | -0.009 |
| | (0.216) | (0.442) | (0.017) | (0.090) |
| Democratic vote, % | 0.021 | 0.035 | -0.004 | -0.021 |
| | (0.032) | (0.066) | (0.003) | (0.020) |
| log(Assets of environmental NGOs, dollars per person) | 0.106 | 0.220 | 0.0009 | -0.005 |
| | (0.192) | (0.400) | (0.022) | (0.121) |
| constant | -19.528*** | | -1.45*** | |
| | (6.280) | | (0.470) | |
| log(σ) log(City population, thousand people) | | | -0.156*** | |
| | | | (0.011) | |
| N | 53 | | | |
| Log likelihood | -13.962 | | | |
| AIC | 61.926 | | | |

Note: Gray infrastructure funding levels are logged values in million dollars adjusted to 2010 price. Columns 1 and 3 report coefficient estimates from maximum likelihood, and column 2 and 4 report the corresponding average marginal effect. Standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

### Table A4.3 Hurdle model of GI adoption for CSO management with outliers removed

| | Selection of GI Program | | Amount of GI Funding | |
|---|---|---|---|---|
| **Variable** | **(1)** | **(2)** | **(3)** | **(4)** |
| 2-year 24-hour precipitation event size, inches | -1.633**<br>(0.675) | -1.779***<br>(0.636) | -0.375**<br>(0.156) | -0.946***<br>(0.347) |
| log(Capital needs for CSO infrastructure, dollars per person) | 0.360<br>(0.224) | 0.520**<br>(0.230) | 0.242***<br>(0.054) | 0.613***<br>(0.146) |
| log(City population, thousand people) | 1.631***<br>(0.478) | 1.740***<br>(0.475) | 0.368**<br>(0.073) | 0.828***<br>(0.286) |
| Median household income, thousand $ | 0.007<br>(0.007) | -0.008<br>(0.033) | -0.017**<br>(0.008) | -0.044**<br>(0.018) |
| Unemployment rate, % | -0.143<br>(0.215) | -0.229<br>(0.197) | -0.126***<br>(0.049) | -0.318***<br>(0.112) |
| Democratic vote, % | 0.020<br>(0.032) | 0.032<br>(0.030) | 0.017*<br>(0.009) | 0.023*<br>(0.023) |
| log(Assets of environmental NGOs, dollars per person) | 0.107<br>(0.192) | 0.025<br>(0.178) | -0.091*<br>(0.045) | -0.229*<br>(0.131) |
| constant | -19.46***<br>(6.309) | | -2.952***<br>(0.099) | |
| log(σ) log(City population, thousand people) | | | -0.098***<br>(0.012) | |
| N | 51 | | | |
| Log likelihood | -16.617 | | | |
| AIC | 67.233 | | | |

Note: GI funding levels are logged values in million dollars adjusted to 2010 price. Columns 1 and 3 report coefficient estimates from maximum likelihood, and column 2 and 4 report the corresponding average marginal effect. Standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

**Table A4.4 Sensitivity of hurdle model to population scale**

| | Selection of GI Program | | Amount of GI Funding | |
|---|---|---|---|---|
| **Variable** | **(1)** | **(2)** | **(3)** | **(4)** |
| 2-year 24-hour precipitation event size, inches | -1.145** | -0.329 | -0.329 | -0.666* |
| | (0.563) | (0.164) | (0.164) | (0.395) |
| log(Capital needs for CSO infrastructure, dollars per person) | 0.372** | 0.277*** | 0.277*** | 0.724*** |
| | (0.182) | (0.052) | (0.052) | (0.143) |
| log(County population, thousand people) | 1.403** | 0.237** | 0.237** | 0.595** |
| | (0.552) | (0.097) | (0.097) | (0.237) |
| Median household income, thousand $ | -0.040 | -0.019** | -0.019** | -0.050** |
| | (0.026) | (0.009) | (0.009) | (0.023) |
| Unemployment rate, % | -0.529* | -0.183** | -0.183** | -0.478*** |
| | (0.283) | (0.072) | (0.072) | (0.178) |
| Democratic vote, % | 0.050 | 0.022** | 0.022** | 0.058** |
| | (0.035) | (0.010) | (0.010) | (0.024) |
| log(Assets of environmental NGOs, dollars per person) | -0.005 | -0.091* | -0.091* | -0.239 |
| | (0.199) | (0.054) | (0.054) | (0.146) |
| constant | -15.39** | | -1.960 | |
| | (7.00) | | (1.489) | |
| log(σ) log(County population, thousand people) | | | -0.085*** | |
| | | | (0.011) | |
| N | 53 | | | |
| Log likelihood | -22.147 | | | |
| AIC | 78.293 | | | |

Note: GI funding levels are logged values in million dollars adjusted to 2010 price. Columns 1 and 3 report coefficient estimates from maximum likelihood, and column 2 and 4 report the corresponding average marginal effect. Standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1

# Chapter 5 Development and psychometric testing of the Rate and Accumulation Concept Inventory

## 5.1 Abstract

A fundamental understanding of rate and accumulation principles is important for educating engineers across all sub-disciplines. A method is needed to assess engineering students' conceptual understanding of these principles and to evaluate instruction. This article describes the development of the Rate and Accumulation Concept Inventory (RACI) instrument and provides an analysis of its validity and reliability, along with a discussion of its use in engineering courses. This instrument is designed to test (1) overall mastery of rate and accumulation concepts, and (2) mastery of these concepts within particular contexts (e.g., mathematics, mass flow, and heat flow). The RACI can also be used to assess curricular interventions aimed at changing students' conceptual understanding of rate and accumulation principles. Exploratory findings on students' conceptual understanding prompted the development of a pilot RACI survey. Two different pilot survey administrations took place, with adjustments made to the instrument between each. Data from the most recent administration (N= 305) are used to assess evidence of validity and reliability through structural equation modeling, multidimensional item response theory, and Cronbach's alpha. Validity and reliability evidence indicates that the RACI can be used to measure students' overall understanding of the concepts identified. Issues of potential construct underrepresentation were uncovered in two of the context categories. The evidence of reliability and validity shows that the RACI may be a useful tool to assess engineering student understanding of rate and accumulation principles. Potential uses of the RACI included measurements of changes in student understanding over time, and the

effectiveness of educational interventions intended to affect understanding. Additional research stages will enhance the validity and reliability of the RACI as a diagnostic tool.

## 5.2 Introduction

There is a growing recognition that many engineering students are not learning as much as instructors assume. Of particular concern are the high numbers of students who leave undergraduate engineering courses with scientifically incorrect ideas related to fundamental processes. This study investigates engineering students' conceptual understanding of rate and accumulation processes in various physical contexts. These processes bring together scientific principles of a particular physical context (e.g., water flow or heat flow) with mathematical models that are used to analyze rates of change and accumulation across system boundaries of interest. Thus, for students to improve their ability to learn about and manage complex systems, they must have a strong conceptual understanding of calculus fundamentals, and then be able to interpret how these fundamentals are associated with real world phenomena.

Examples of rate and accumulation processes are mass and energy balances, which are conceptual models used by engineers in many disciplines and contexts. These models are used in structural analysis by civil and mechanical engineers, heat-work relationships by chemical engineers, and fate and transport modeling by environmental engineers. These processes are also used in so-called "stocks and flows" problems by engineers in different types of design problems. Research shows that most people's intuitive understanding of stocks and flows is poor, and student misconceptions related to rate and accumulation processes have been known for some time (Carlson et al., 2003; Sweeney and Sterman, 2000, 2007; Thompson, 1994a). Students may form misconceptions of rate and accumulation processes for numerous reasons. For example, certain focusing phenomena used in the classroom have been linked to students incorrectly generalizing slopes as differences in quantities rather than ratios (Lobato et al., 2003).

Knowing how students think and learn about rate and accumulation processes in complex systems can help educators better prepare students for their engineering careers. This paper describes the development of the Rate and Accumulation Concept Inventory (RACI), which was designed to address the need for an assessment tool to measure student understanding of rate and accumulation processes across multiple contexts. While many concept inventories have been developed to assess students' understanding of either mathematical principles or scientific concepts related to particular topics, the RACI combines these both of these important types of understanding in one assessment tool. This article presents a psychometric analysis of the RACI to ascertain its viability as a research instrument. We begin with a background on conceptual understanding and psychometric analysis before applying those theories to the evaluation of the RACI. Finally, we conclude with recommendations for the refinement of the RACI and its appropriate current uses.

## 5.3 Theoretical Basis

Several decades of research have led to different approaches to assessing conceptual understanding in students. We will present literature on conceptual understanding and highlight key methods on developing and analyzing concept inventories. We then summarize the exploratory work that demonstrated the need for the inventory, followed by a discussion of the development of the conceptual categories and question items included in the RACI.

### 5.3.1 Conceptual understanding

*Conceptual understanding* refers to an individual's collection of concepts (i.e., pieces or clusters of knowledge), beliefs (i.e., propositional relationships between concepts), and mental models (i.e., groups of meaningfully related beliefs and concepts that allow one to explain phenomena and make predictions) related to a particular topic (Streveler et al., 2014). *Conceptual change*, defined as the process of altering some aspect of one's conceptual understanding to be consistent with scientific understanding, has long been recognized as a fundamental aspect of learning (Duit and Treagust, 2003; Mayer, 2002). Constructivism provides a foundation for research of conceptual change, as it implies that one's pre-existing knowledge affects how new knowledge is encountered (Fosnot and Perry, 1996; Piaget, 1973; Von Glasersfeld, 1989; Vygotsky, 1980). Thus, how a student acquires new knowledge can be affected by *misconceptions*, which we define as some aspect of one's conceptual understanding that is different from what is known to be scientifically or mathematically correct (sensu National Research Council, 2012).

Several prominent theories exist which seek to describe the structure of students' conceptual understanding related to particular topics. Many researchers propose that conceptual understanding exists as coherent categorizations of one's concepts, beliefs, and mental models, which can be organized along shared properties (Carey, 1985; Chi et al., 2012; Chi and Roscoe, 2002; Clement, 1983; McCloskey, 1983; Vosniadou, 2007, 1994; Vosniadou and Brewer, 1992; Vosniadou et al., 2008). This view suggests that students maintain stable ways of thinking about a particular topic (including misconceptions) because their knowledge is structured in coherent or theory-like ways. Alternatively, knowledge can be understood as separate pieces of intuitions based on experiences, which one can learn to relate and establish meaningful relationships (diSessa, 2008, 2002, 1988; Minstrell, 2001). Thus, the “knowledge in pieces” theory (diSessa, 1983) posits that a students’ conceptual understanding on a topic is comprised of phenomenological primitives (p-prims), which are self-explanatory schemata that are generally apparent to people in real-world contexts. In this sense, our definition of a misconception could be interpreted as a misapplication of a p-prim. Furthermore, conceptual change would require corresponding p-prims to be re-contextualized to create normative conceptual understanding (diSessa, 2008).

While there are key differences in these two views, there is strong evidence for them both and they are not necessarily incompatible (Özdemir and Clark, 2007). Several researchers have argued that both models are needed to fully explain conceptual understanding (Hammer, 1996; Taber, 2008). For instance, Brown and Hammer (2008) propose a conceptual system in which cognitive structures arise from the interactions of smaller conceptual elements similar to p-prims. The tension between these views can also be construed as a question of that grain size of the conceptual understanding elements that are studied (diSessa, 2008). How conceptual understanding is structured has important implications for how conceptual understanding is assessed in the RACI, which is discussed below.

### 5.3.2 Concept Inventories and Development of the RACI

Assessing engineering students’ conceptual understanding before a course begins can provide instructors with valuable feedback. Concept inventories are assessment instruments that have been used in several math, science, and engineering disciplines as a way to provide reliable and valid assessment of students’ misconceptions. The work of Hestenes et al. (1992) on the Force Concept Inventory established many of the protocols for concept inventory development, which have since been further established by many authors (Adams and Wieman, 2011; Steif and Dantzler, 2005; Streveler et al., 2011, 2003).

One of the most critical issues in developing a concept inventory is the process used to establish content validity. Several educational measurement theorists argue that test validation should involve iteration that begins with evidence-based approaches to determine the constructs worthy of assessment (Kane, 2013; Lissitz and Samuelsen, 2007). For example, the “assessment triangle” (Pellegrino et al., 2014, 2001) is an evidence-based framework for instrument development that consists of three underlying elements: cognition, observation, and interpretation. First, a model of student cognition and learning should be developed that demonstrates how students represent and develop new knowledge on a topic. Second, observable tasks or situations must be identified that allow a researcher to observe students’ performance and provide evidence of their competencies. Third, a method must be established for interpreting the performance evidence.

The assessment triangle framework is used to describe the iterative process used in the development of the RACI. We developed the current version through four stages of research (Table 5.1). The concept inventory development steps suggested by Richardson (2005) and analytical framework suggested by Jorion et. al (2015) also provided insight on the data collection and analytical methods at each stage. Past findings from stages 1-3 are summarized below, and new findings for research stage 4 are discussed in this paper.

**Table 5.1 Research stages and strategies for RACI development**

| Research Stage | Assessment Triangle Corner(s) | Data Collection Methods | Analytical Methods | Resulting Actions |
|---|---|---|---|---|
| 1. Exploratory Work | Cognitive | • Open ended survey instruments based on class activities<br>• Video and audio recordings of student work | • Rubric scoring of surveys<br>• Pre- & post- testing of surveys<br>• Line-by-line transcript analysis | • Articulate concepts to assess in new instrument |
| 2. Instrument Development | Observation | • Construct initial RACI, using open-ended questions for untested items | • Content validity testing | • Begin pilot testing |
| 3. Pilot study #1 | Observation and Interpretation | • RACI administered to small population<br>• Interviews | • Rubric scoring of open ended question items<br>• Preliminary validity and reliability testing | • Design multiple-choice answers<br>• Revise, delete, add items |
| 4. Pilot study #2 | Interpretation | • RACI administered to larger population | • Classical test theory and item response theory analyses<br>• Exploratory factor analysis, tentative confirmatory factor model | • Formulate tentative factor analysis model<br>• Revise, delete, add items |

### 5.3.2.1 Stage 1: Cognitive Basis

Our study began in an urban hydrology unit that is part of a sophomore course entitled “Sustainability in Civil and Environmental Systems” that is required for all civil engineering and environmental engineering undergraduate majors at a university in the Northeast U.S. Several methods were used to study student learning of engineering concepts related to water flow processes. We first developed original survey instruments to assess student understanding of two topics: first order calculus and water flow. Multiple representations of understanding were assessed in the survey questions, including equations, graphs, mental models, and descriptions. Video and audio recordings of student activities were analyzed to identify patterns in students' discourse. These findings were triangulated with the survey results to draw inferences about students' conceptual understanding. Results suggested the existence of persistent misconceptions among the students, specifically the inability to distinguish between rate and accumulation processes (Flynn et al., 2014).

A key finding was that many students often struggled to understand fundamental scientific concepts relating to a particular physical context, and had difficulty correctly using mathematical models when analyzing rate and accumulation processes. This led us to develop a theoretical cognitive model, in which students have a broad conceptual understanding of rate and accumulation problems that is shaped by mathematical understandings and scientific understandings (Figure 5.1).

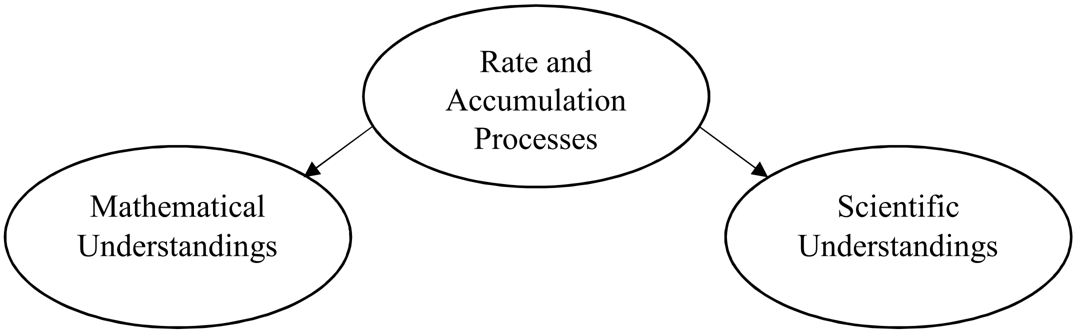

**Figure 5.1 Path diagram showing generalized hypothetical cognitive model for rate and accumulation understanding**

Mathematics education has long been considered to exist in a different domain of learning from physical sciences. This view stems from the argument that since mathematics is based on deductive proofs and not on experiments, it should be separated from the empirical pattern of scientific development and change (Kuhn, 1962). However, it can be argued that the conceptual change theories for scientific understanding can be successfully applied to mathematics learning (Vosniadou, 2008), as math students have been found to develop naïve presuppositions that affect learning much like in the physical sciences (Dehaene, 2011; Gelman, 2000; Lipton and Spelke, 2003).

Many studies have investigated the relationships between mathematical and scientific abilities and understandings. A study by Meltzer (2002) suggested that students' pre-instruction algebra skills may be associated with their ability to gain physics conceptual knowledge. Similarly, Wage, Buck, and Wright (2005) used correlations between student scores on the Signals and Systems concept inventory and grades in prerequisite mathematics courses to claim that the mathematical understanding of students contributes to conceptual learning of signals and systems concepts. Fewer studies have investigated the way in which a scientific or mathematical context can affect a student's understanding. Potgieter et al. (2008) investigated whether student difficulties in undergraduate chemistry problems were due to deficiencies in their mathematics understanding or the complexity of transferring mathematical understanding to a scientific domain, concluding that fundamental mathematical understanding was the primary issue for most students. Jones (2015) examined students as they applied their mathematical knowledge to science and engineering problems by examining their definite integral conceptualizations in both a pure mathematics and an applied physics context, finding that a Riemann sum-based conceptualization was highly productive in applied contexts.

There may be many complex conceptual elements that shape a student's scientific or mathematical understanding of rate and accumulation problems. For instance, students should be proficient with their mathematical understandings of variables, functions, differentiation, and integration. Mathematical misconceptions of rate of change and accumulation processes have been well researched (Ärlebäck et al., 2013; Carlson et al., 2003; Confrey and Smith, 1994; Doerr et al., 2013; Thompson, 1994a, 1994b; Thompson and Silverman, 2008; Zandieh, 2000). There is evidence that students have weak understandings of the concepts of variables (Martin, 2000; White and Mitchelmore, 1996), the concepts of functions (Carlson, 1998; Confrey and Smith, 1994; Monk, 1992; Oehrtman et al., 2008), and covariational reasoning, or the ability to coordinate two varying quantities while attending to how they change in relation to each other (Carlson et al., 2002). Many science and engineering education studies have shown that students frequently confound physical factors involved in rate and accumulation problems. For instance, rate of change and accumulation misconceptions have been identified in studies on energy transfer (Miller et al., 2006; Prince et al., 2012), chemical reactions (Thomas and Schwenz, 1998), and induced current (Thong and Gunstone, 2008).

### 5.3.2.2 Stage 2-3: Observation Basis and Initial Interpretation

Work began on the development of an assessment tool that would assess students' conceptual understanding of rate and accumulation processes. Several existing concept inventories were considered for their suitability as assessment instruments (Gray et al., 2005; Martin et al., 2003; Shallcross, 2010). While some of these inventories include questions to assess student understanding of particular rate and accumulation processes, they tend to be context-specific for particular science and engineering disciplines. Because rate and accumulation processes represent a fundamental conceptual framework that spans many engineering disciplines, the RACI is not intended to be a discipline specific concept inventory.

The preliminary concepts included in the first beta-version of the RACI were identified using the cognitive basis study results and a literature review of rate and accumulation conceptual understanding in other engineering disciplines. Three categories of concepts were included: (1) mathematical understandings of first order calculus, (2) physical factors involved in mass flow, and (3) physical factors involved in heat flow. Ten sets of questions were included with thirty individual question items in total. The questions were designed to be representative of knowledge that students would be expected to know after a first-year coursework in calculus and physics. Two question sets were modified problems from an introductory calculus textbook (W. Briggs and L. Cochran, 2010). These questions were included to assess students' ability to interpret rate and accumulation processes using graphical representation of rate of change functions. A third calculus question set was adapted from research that investigates students' covariational reasoning abilities (Carlson et al., 2002). The mass flow category included original inventory items developed from the exploratory study over a number of iterations with several engineering instructors and graduate students. These question items were designed to assess student understanding of physical principles that define water flow processes. While student understanding of heat flow principles was not directly tested in Stage 1 of our research, several studies have shown that students frequently confound factors that affect energy transfer rates with those that affect the total amount of energy transfer (Miller et al., 2006; Prince et al., 2012). The heat flow question items for the RACI were taken directly from a rate and accumulation processes subsection of the Heat and Energy Concept Inventory, developed by Prince et al. (2012) with the primary author's permission. Two of these question items were designed to assess mass flow principles, and were categorized as such in the study analysis.

Questions item formats were open-ended unless the question had been previously developed and assessed for its validity and reliability. The open-ended questions allowed for the collection of a range of student reasoning responses for each question. Incorrect responses were categorized by multiple graders according to the type of misconception suggested in the students' work. These categories were then combined into a single rubric for the grading of each question. Confidence ratings were also included to assess potentially confusing or overly difficult problems. Initial pilot testing of the RACI using a pre- and post-course testing scheme indicated persistent misconceptions across multiple contexts. Internal consistency reliability was assessed on an earlier version of the RACI using the Kuder-Richardson Formula 20. This yielded a value of 0.77 for the instrument and ranges of 0.64 to 0.76 for the three contextual categories (Flynn et al., 2015), suggesting satisfactory consistency. Structural analysis was not completed during this stage of research, as the study populations were low (N=75).

## 5.4 Study Goal

Misconceptions of scientific and mathematical principles related to rate and accumulation processes is widespread across many disciplines, and thus a concept inventory on rate and accumulation processes across several contexts is warranted. Such an inventory can help instructors design pedagogical interventions that will enhance student learning on these principles. The objective of this research is to provide instructors a tool to measure the degree to which a student's misconceptions of rate and accumulation processes is related to mathematical understandings of rate of change problems and physical understandings of particular processes, such as water flow and heat flow processes. Specifically, the primary goals of the RACI are to assess (1) overall mastery of rate and accumulation concepts, and (2) mastery of these concepts within particular contexts. This paper describes reliability and validity testing of the RACI that was conducted to assess the degree of support for these goals. Results from a recent pilot test are used to assess the validity and reliability of question items and concept categories. The analysis methodologies suggested by the Evidentiary Validity Framework (Jorion et al., 2015b) are used to assess the validity of each of the primary goals of the RACI. Methods to assess claim 1 include classical test theory methods (Cronbach's alpha, standard error of measurement, alpha-if-item-deleted, item discrimination, and item difficulty) and item-response theory tests. Methods to asses claim 2 include subscale alphas and factor analyses. Table A5.1 in Appendix A5 includes criteria used for the qualitative judgments that were assigned for rating each test.

## 5.5 Results

### 5.5.1 Stage 4: Interpretation Basis

Phase 4 of the RACI development aims to continue the improvement of the RACI's validity, reliability, and fairness. The results of Phase 3 led to the development of a second pilot version of the RACI (referred to as "RACI 2.0"), which began with the refinement or removal of several question items. The rubric for scoring in the initial development phase was used to develop multiple choice answers, including "distractor" choices, for each question item. RACI 2.0 includes additional question items from the Precalculus Concept Assessment instrument that are identified as "rate and accumulation" questions (Carlson et al., 2010), with the author's permission. In total, RACI 2.0 includes 25 question items. Five sets of questions are two-tiered, in that two related question items are presented as a factual question followed by a conceptual question. For this analysis, two-tiered sets of question items are coded as correct when both question items are correctly answered. Five sets of two-tiered question items followed this coding scheme; thus, the total possible score for RACI 2.0 is 20. Confidence ratings were removed from the RACI 2.0 pilot test to reduce test taking time requirements. Test questions for RACI 2.0 are include in Appendix A5.

A taxonomy of the RACI was developed (Table 5.2) to synthesize the understandings and abilities that are included in the RACI question items. The subscales used in the Precalculus Concept Assessment taxonomy (Carlson et al., 2010) provided a basis for some of the RACI taxonomy. While most mathematical questions on the RACI are presented within a physical context, such as a person walking in a line or water filling a particular shape, the questions are not designed to test scientific principles related to the particular context. Four question items (1a, 1b, 5 and 9) feature water flow as a representative rate of change process but are identified in the mathematical concept category, as they require no knowledge of the physical properties related to water flow. Several question items require multiple types of reasoning abilities and functional representations. As categories for items are not mutually exclusive, they are not analyzed as unique subscales within the RACI.

**Table 5.2 Taxonomy of RACI subscales and corresponding question items**

| | **Subscale** | **Questions** | **Total question score** |
|---|---|---|---|
| **Reasoning Abilities** | Process view of function items | 1a, 1b, 2a, 2b, 2c, 3, 4, 6, 9 | 9 |
| | Covariation reasoning | 1a, 2a, 2b, 2c, 3, 5, 7, 8, 10, 12, 13.1, 13.2, 14, 15a, 15b | 12 |
| | Computational abilities | 1a, 1b, 2a, 2b, 2c, 4, 9 | 7 |
| **Functional Representations** | Graphical | 1a, 1b, 2a, 2b, 2c, 3, 5, 7, 9 | 9 |
| | Equation | 4, 6, 9 | 3 |
| | Descriptive | 8, 10, 11, 12, 13.1, 13.2, 14, 15a, 15b | 9 |
| **Concept Category** | Mathematics | 1a, 1b, 2a, 2b, 2c, 3, 4, 5, 6, 7, 9 | 11 |
| | Mass flow | 8, 10, 11, 12, 15a, 15b | 6 |
| | Heat flow | 13.1, 13.2, 14 | 3 |

The Stage 4 pilot test population includes students from a variety of disciplines enrolled in either a sophomore or junior level class engineering course (Table 5.3). Tests were administered in eight courses across three private universities in the Northeast U.S. in 2015 or 2016 using a pre-course and post-course testing scheme. Pre-course tests were given in the first two weeks of a course, and post-tests were given in the final two weeks of a course. Pre-course and post-course tests were collected for all but two courses, in which only post-tests were collected. The post-test population is used for the reliability and validity testing due to the larger number of respondents (N=305).

**Table 5.3 Stage 4 study population demographics**

| | | **Post-test Responses (N=305)** |
|---|---|---|
| **Major** | Civil | 124 (40.7%) |
| | Chemical | 35 (11.5%) |
| | Environmental | 61 (20.0%) |
| | Mechanical/Aerospace | 63 (20.7%) |
| | Other | 22 (7.2%) |
| **Academic Level** | Sophomore | 192 (63.0%) |
| | Junior | 63 (20.7%) |
| | Senior | 43 (14.1%) |
| | Other | 7 (2.3%) |
| **Gender** | Female | 52 (17.0%) |
| | Male | 252 (82.6%) |
| | Nonbinary | 1 (0.33%) |
| **GPA** | Cumulative GPA | 2.70 |

**Table 5.4 Summary statistics**

| | Total Possible Score | Mean | Standard Deviation |
|---|---|---|---|
| **Mathematics** | 11 | 6.55 (59.6%) | 2.39 |
| **Mass flow** | 6 | 2.55 (42.5%) | 1.30 |
| **Heat flow** | 3 | 0.73 (24.5%) | 0.92 |
| **Overall** | 20 | 9.84 (49.2%) | 3.48 |

### 5.5.2 Classical Test Theory

Table 5.4 summarizes the results for the overall test and the three concept categories. The mean observed score was 9.84 out of 20 points, or 49.2%. The overall Cronbach's alpha value is 0.70, indicating an average level of reliability as an overall assessment tool. Table 5.5 summarizes the question item difficulty, discrimination, and Cronbach's alpha value for the RACI if the item is deleted. Four question items had alpha-if-deleted values equal to or greater than the overall test alpha (Q1b, Q11, Q13.2, and Q15b).

**Table 5.5 Summary of classical test theory values for question items. Bolded numbers indicate a value that does not meet recommended threshold criteria**

| Item | Item Difficulty | Item Discrimination | Alpha-if-deleted |
|---|---|---|---|
| Q1a | 0.65 | 0.46 | 0.69 |
| Q1b | 0.89 | 0.18 | **0.71** |
| Q2a | 0.75 | 0.40 | 0.69 |
| Q2b | 0.50 | 0.48 | 0.68 |
| Q2c | 0.70 | 0.36 | 0.69 |
| Q3 | 0.45 | 0.58 | 0.67 |
| Q4 | 0.53 | 0.35 | 0.69 |
| Q5 | 0.48 | 0.39 | 0.69 |
| Q6 | 0.48 | 0.42 | 0.69 |
| Q7 | 0.80 | 0.47 | 0.68 |
| Q8 | 0.28 | 0.41 | 0.69 |
| Q9 | 0.33 | 0.34 | 0.69 |
| Q10 | 0.90 | 0.30 | 0.69 |
| Q11 | 0.22 | 0.20 | **0.71** |
| Q12 | 0.47 | 0.39 | 0.69 |
| Q13.1 | 0.29 | 0.41 | 0.69 |
| Q13.2 | 0.09 | 0.27 | **0.70** |
| Q14 | 0.35 | 0.60 | 0.67 |
| Q15a | 0.40 | 0.39 | 0.69 |
| Q15b | 0.29 | 0.27 | **0.70** |

Figure 5.2 compares the difficulty and discrimination values for each item. Question item Q13.2 fell below the recommended difficulty level but not for discrimination. Other item difficulties ranged from 0.22 to 0.89. One item fell slightly below recommended values for discrimination (Q1b), while other discrimination values ranged from 0.210 to 0.654.

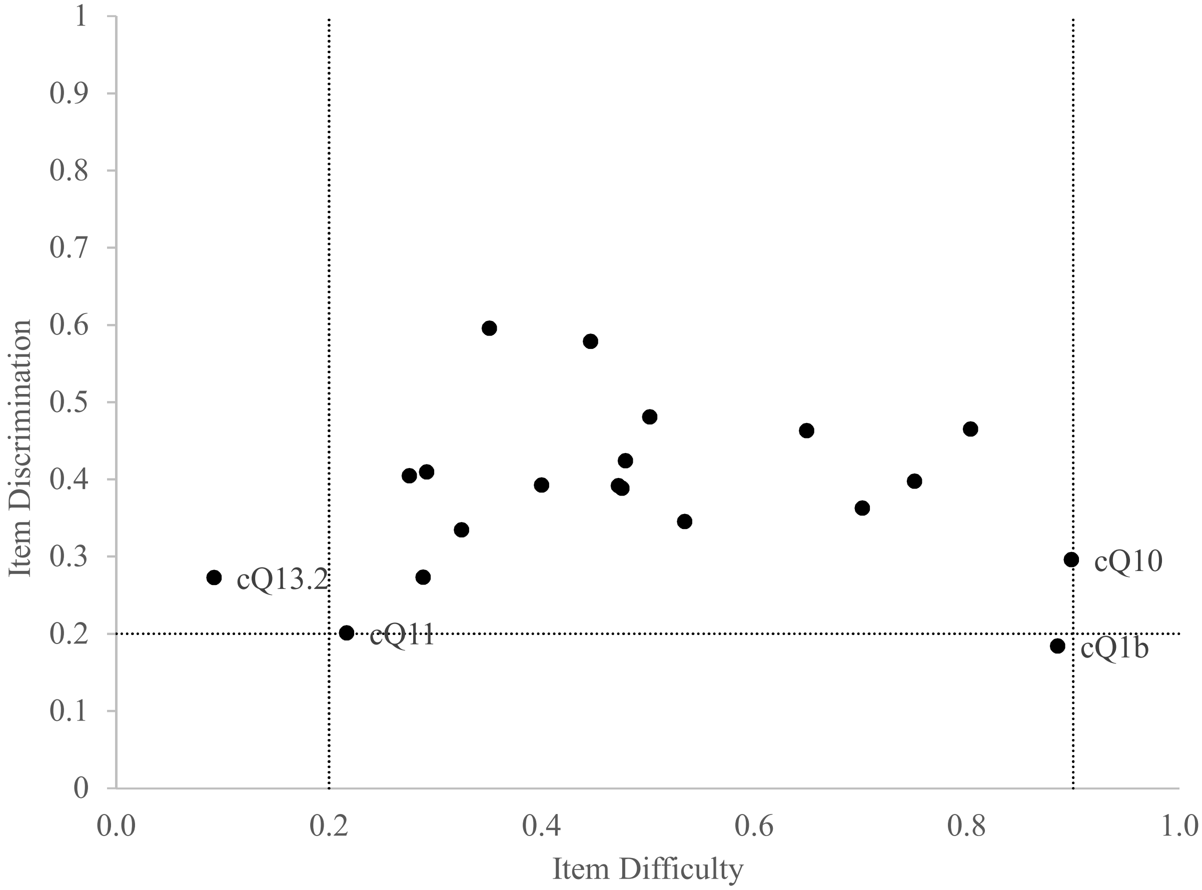

**Figure 5.2 : Scatterplot of item difficulty and discrimination values for RACI 2.0. Each dot represents an individual question item or grouped two-tier question. Recommended minimum and maximum values are denoted by the dotted lines. One item did not meet the recommended values for difficulty (Q13.2) and one fell below the recommended value for discrimination (Q1b).**

### 5.5.3 Item Response Theory

Item response theory analyses were performed using one-parameter, two-parameter, and three-parameter logistic models. The models were compared with the Akaike information criterion fit statistic, with the two-parameter model resulting in the best fit. Figure 5.3 shows the two-parameter item response functions as indicated by the cumulative probability of answering an item correctly across the students' proficiency (theta) scale, i.e., the latent trait continuum. In general, the curves begin with low values of student ability and rise with increasing probabilities of answering the item correctly along with increasing student ability. The theta location at the inflection point of the curve indicates the item's degree of difficulty. The two-parameter model includes both estimated difficulty and discrimination parameters, allowing curves to have different slopes. Steeper slopes indicate higher levels of discrimination across student abilities. The majority of question items demonstrated close model-data fit, with the exception of items Q1b, Q11, and Q13.2, and Q15b. Item Q10 also has a weaker fit for the post-course populations, as it was found to have a lower level of difficulty than other questions.

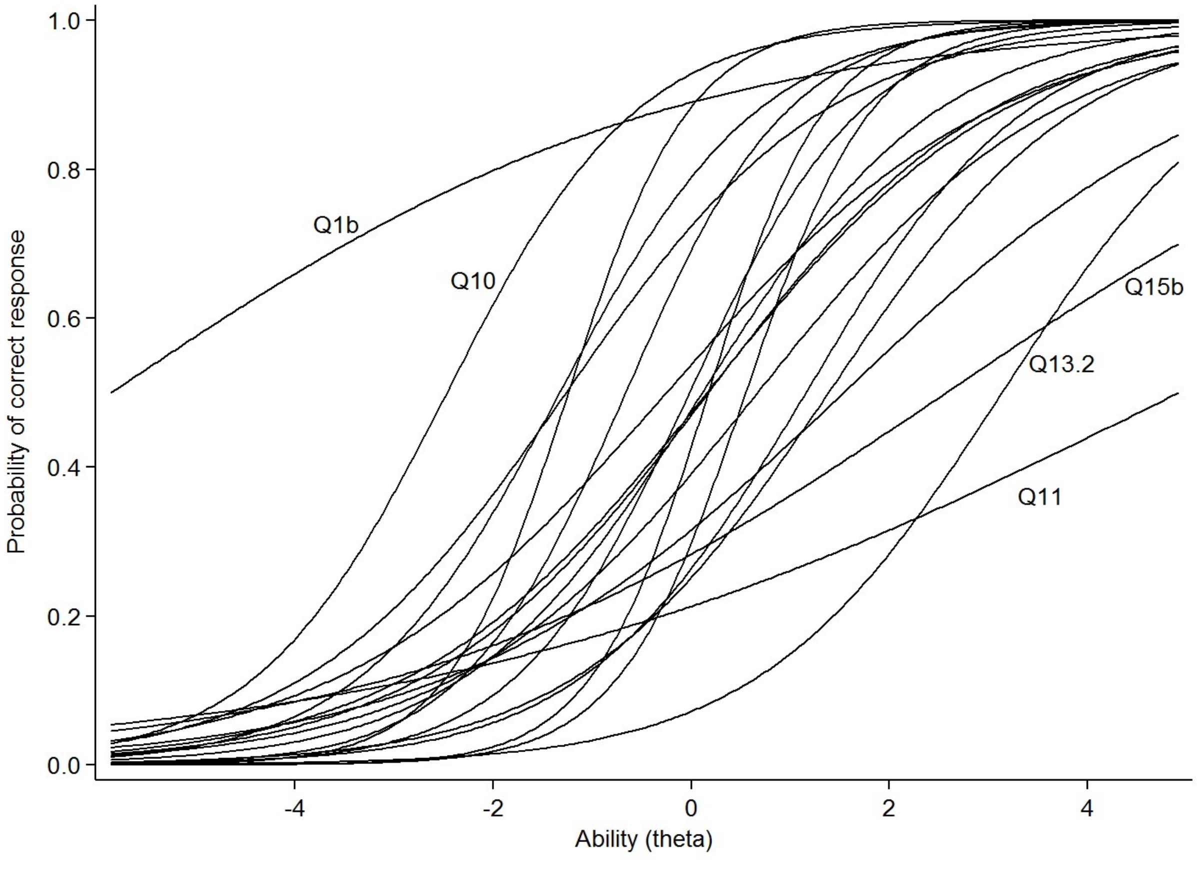

**Figure 5.3 Two-parameter item response function for all post-test RACI 2.0 question items. Two items (Q1b and Q11) deviate from the standard model shape, while other items generally fit the two-parameter model well. Question items Q13.2 and Q15b were among the more difficult question items, but generally conform to the shape of the model.**

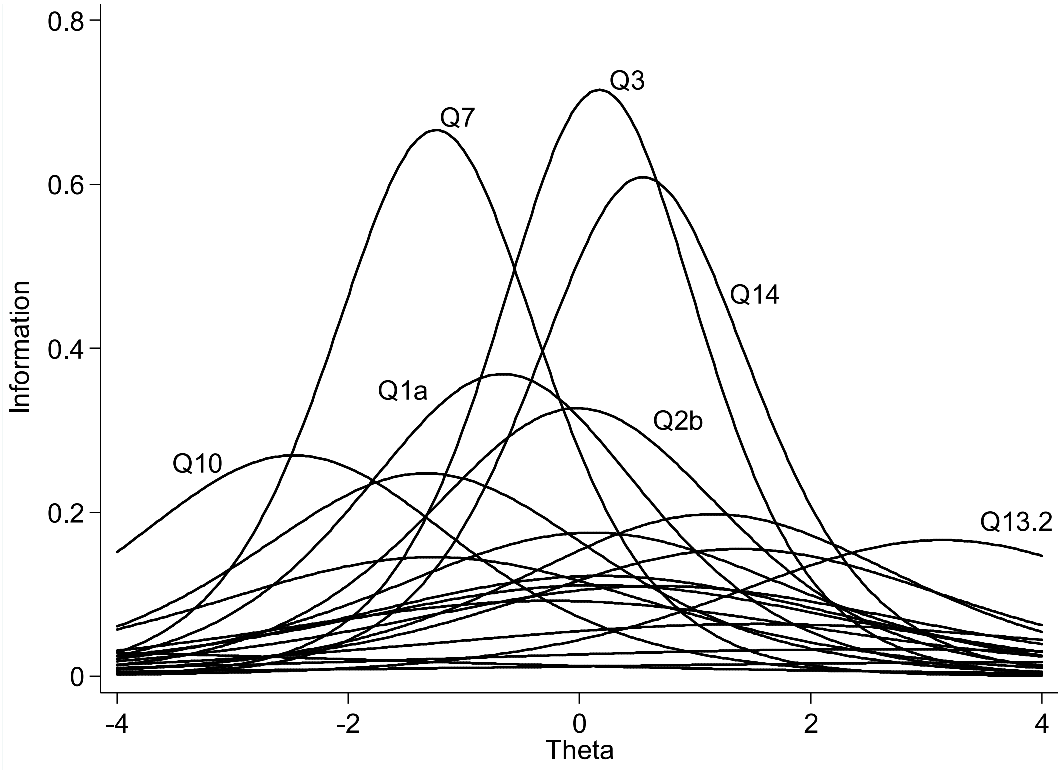

**Figure 5.4 Two-parameter item information function for all post-test RACI 2.0 question items.**

The item information function for the RACI is shown in Figure 5.4. As scores for each item are binary, the amount of information each question item provides is proportional to the discrimination parameter. Items Q3, Q7, and Q14 provide the most information for this study population. The results reiterate the overall weak discrimination power of item Q10, other than for students who performed poorly (i.e. those with a lower theta). Similarly, item Q13.2 only provided useful discrimination information for higher performing students. As the majority of this pilot test population includes sophomore engineering students who may not have been exposed to heat flow concepts, item 13.2 may be too difficult for certain populations and teaching contexts.

The item information functions are summed to obtain a test information function (Figure 5.5). This plot shows how well the instrument can estimate person locations. The test information curve peaks at an approximate theta value of zero, suggesting that the RACI provides the most information for average students. As the curve moves away from that point in either direction, the standard error of the test information function increases, and the instrument provides less and less information about student understanding.

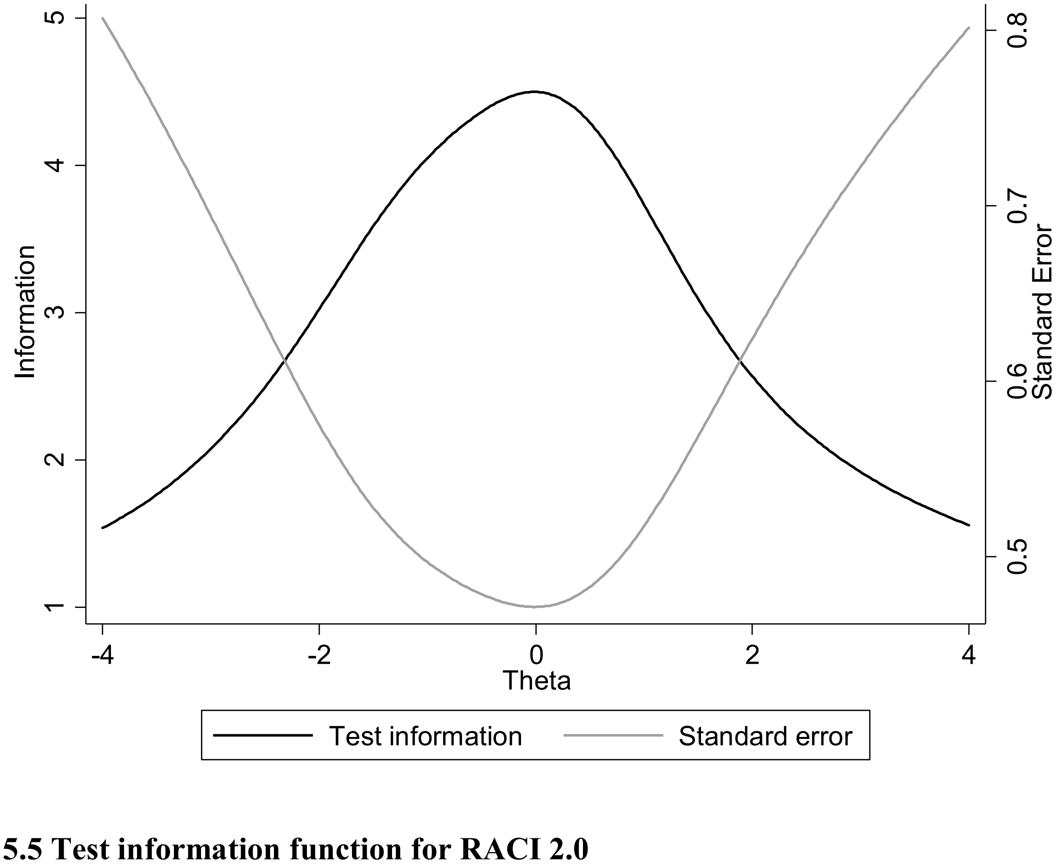

**Figure 5.5 Test information function for RACI 2.0**

On the basis of the item testing analysis, two items were removed for the structural analyses: Q1b and Q11. Both items had higher alpha-with-item-deleted values and did not fit well in one or both pre-course and post-course information response models. The results suggest that the current form Q1b may be too easy compared to other RACI items, while Q11 may be misleading and thus would require revision in subsequent versions of the RACI. Item 13.2 and item 15 did not have excellent results in the item testing analysis but were retained for the structural analysis to test if they fit well with the theoretical constructs of the RACI.

## 5.5.4 Structural Analysis

### *5.5.4.1 Tetrachoric Correlation*

Covariation among item responses is used as an initial analysis of the possible underlying structure within the RACI. Tetrachoric correlations constitute an adjusted version of Pearson correlations that are appropriate for pairs of items discretely scored right/wrong (Bonett and Price, 2005). The RACI item-pair tetrachoric correlations are shown graphically by a heat map for the study population (Figure 5.6). The heat map matrix is symmetric, and items are ordered according to the three contextual RACI concept categories. The pattern of tetrachoric correlations shown in Figure 5.6 indicates the strongest correlations in the Heat Flow subscale. Correlations are moderately strong among question items in the Mathematics subscale, particularly among Q1a-Q3. Question items Q8-Q12 in the Mass Flow subscale also showed moderate correlations, while Q15a and Q15b were among the weaker correlations within the Mass Flow subscale and across all other question items. Two other outlying items are Q9, which has weak correlations with all other items, and Q14, which is moderately correlated with many items in other subscales.

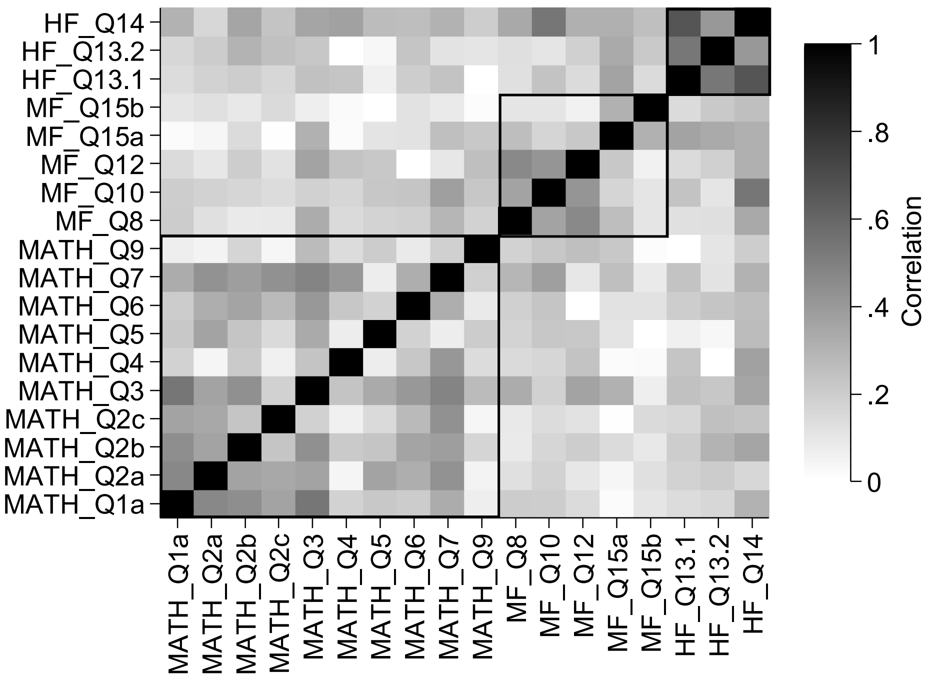

**Figure 5.6 Tetrachoric correlation heat map for the RACI 2.0. Darker shaded squares indicating strong correlations between correctly answered items. Question items are grouped according to their conceptual subscale category (MATH = Mathematics, MF= Mass Flow, and HF=Heat Flow) with borders added to interpret these theoretical groupings.**

### *5.5.4.2 Subscale Alphas*

Subscale reliabilities (Cronbach's alphas) were estimated for each of the three context subscales using the post-course population (Table 5.6). Individual subscale alpha values ranged from 0.42 to 0.65. Because Cronbach's alpha is influenced by test length, lower values of subscale alphas may result in part from small numbers of items per subscale.

**Table 5.6 Cronbach's alpha for RACI subscales**

| Concept Context Subscale | Alpha | Number of Question Items |
|---|---|---|
| **Mathematics** | 0.65 | 10 |
| **Mass Flow** | 0.42 | 5 |
| **Heat Flow** | 0.57 | 3 |

#### *5.5.4.3 Exploratory Factor Analysis*

An exploratory factor analysis (EFA) was performed to assess the dimensionality and structure of the RACI. The primary goals of an EFA are to determine the number of factors underlying the variation in and correlations among the items and to identify items that load onto particular factors (Thompson, 2004). Items that do not load onto any of the extracted factors, or that cross-load onto multiple extracted factors, may be considered for removal from the RACI.

Results for the EFA using the post-course populations are presented in Table 5.7. A parallel analysis (Horn, 1965) indicated that a three-factor structure was optimal, which accounts for 80% of the total variance. An oblique rotation was performed under the assumption that the factors are correlated. Very poor factor loadings (less than 0.32) were suppressed to allow for ease of interpretation (Comrey and Lee, 1992; Tabachnick and Fidell, 2013). The overall Kaiser-Meyer-Olkin measure suggested that the sample size is sufficient for the structural analysis (Kaiser, 1974). Inter-factor correlations are shown in Table 5.8.

**Table 5.7 Exploratory factor analysis for RACI 2.0**

| Question Item | Subscale Factor Loadings | | |
|---|---|---|---|
| | Mathematics | Heat Flow | Mass Flow |
| Q1a | 0.68 | | |
| Q2a | 0.77 | | |
| Q2b | 0.57 | | |
| Q2c | 0.55 | | |
| Q3 | 0.57 | | |
| Q4 | | | |
| Q5 | | | |
| Q6 | 0.51 | | |
| Q7 | 0.64 | | |
| Q9 | | | 0.34 |
| Q13.1 | | 0.85 | |
| Q13.2 | | 0.68 | |
| Q14 | | 0.64 | |
| Q15a | | 0.45 | |
| Q15b | | 0.32 | |
| Q8 | | | 0.56 |
| Q10 | | | 0.64 |
| Q12 | | | 0.70 |

**Table 5.8 Inter-factor correlation matrix**

| **Factor** | **Factor Name** | **1** | **2** | **3** |
|---|---|---|---|---|
| **1** | Mathematics | 1 | | |
| **2** | Heat Flow | 0.379 | 1 | |
| **3** | Mass Flow | 0.359 | 0.313 | 1 |

Most question items loaded onto the predefined conceptual subscales, and thus the conceptual subscale names are presented for the three factors in Table 5.7. However, there are several exceptions. Two question items (Q4 and Q5) did not have strong loadings on any of the factors. Three items loaded on unexpected factors (Q9 on Mass Flow, Q15a and Q15b on Heat Flow), though these loadings are the lowest of the retained factor loadings and thus account for little of the overlapping variance.

We believe there are several interpretations for these unexpected loadings. Messick (1995) notes two threats to instrument validity are (1) construct underrepresentation, in which an instrument does not actually represent what it is designed to measure; and (2) construct irrelevant variance, in which something other than the actual measured trait is influencing results (Douglas and Purzer, 2015). It is likely that items Q4, Q5 and Q9 have poor results in the factor analysis due to construct irrelevant variance, as students must use overlapping reasoning abilities and understandings to answer these items (see Table 5.2 for classifications). Without these items, the only item in the Mathematics category that does not involve covariational reasoning is Q6; thus, this category may be dominated by this particular mathematical understanding. Furthermore, because all question items in the Mass Flow and Heat Flow categories also assess covariational understanding, it is possible that this is the predominant concept of rate and accumulation understanding that is assessed in the RACI.

There are several interpretations for the unexpected loadings for Q15a and Q15b. First, there may be a level of contract irrelevant variance due to the style of question wording effecting student responses. Because these items are derived from the same concept inventory as all other items in the Heat Flow subscale, there may be subtle differences in question wording that prompt students differently than other items. There may also be several interpretations for construct underrepresentation. One possibility is students interpret the context for these items (a solution of dye being absorbed by sponges) as more similar to that of heat flow, and thus use similar understandings to think about the problem. Alternatively, a closer examination of the physical factors involved in the processes for both the Mass Flow and Heat Flow categories reveal interesting patterns. The problem context for question items Q8 and Q12 focus on two physical factors related to water flow, namely water column height and drain size, while the contexts for the processes presented in question items Q13.1, Q13.2, Q14, Q15a, and Q15b focus on how the physical factors of surface area, amount, and gradient influence heat and mass transfer. Thus, the exploratory factor results may point to issues of construct underrepresentation due to categories labeled for physical context rather than the physical understandings that students are using when answering these items. Recategorizing items Q15a and Q15b as Heat Flow problems slightly lowers the Heat Flow subscale Cronbach's alpha to a value of 0.56, but increases the Mass Flow subscale alpha significantly to a value of 0.65.

#### *5.5.4.4 Tentative Confirmatory Factor Analysis*

A confirmatory factor analysis was performed to explore the extent to which the item covariances conformed to the hypothesized cognitive model for rate and accumulation understanding. Two models were considered in this analysis. Model 1 (Figure 5.7) represents an independence model, in which the subgroups of concepts and their associated items are completely separable. Model 2 (Figure 5.8) represents a higher-order factor model that reflects our hypothesis that students have a broad conceptual understanding of rate and accumulation processes that shapes performance on all concepts and items. Factor analyses were conducted for two additional models in order to investigate findings from the exploratory factor analysis. In Model 3, question items Q15a and Q15b are recategorized to the Heat Flow factor, as both items loaded on this factor in the exploratory analysis. Finally, Model 4 uses the categorizations in Model 3, but eliminates question items that did not load on any factor (Q4, Q5, and Q9). Results for the confirmatory factor analysis are presented in Table 5.9. Factor loadings using standardized regression weights are shown on the paths in Figures 5.7 and 5.8 for Models 1 and 2, respectfully.

For Model 1, most items have moderate loading scores (> 0.3) with the exception of items Q15b and Q13.2. All loadings are significant at the p=0.01 level with the exception of items Q9 and Q10, which are significant at the p=0.05 level, and Q15b, which was not found to be significant in this model. Model 1 did not display strong fit to the data, with most indexes falling below recommended cutoff values.

In Model 2, most items have moderate factor loading scores (> 0.3) with the exception of items Q4 and Q9 on MATH, and Q15b on MF. All loadings were significant at the p=0.01 level with the exception of item Q15b, which was significant at the p=0.05 level. Relations between three conceptual subscales (MATH, MF, and HF) are explained by their shared variance with the higher order factor (RA). All three subscales had very good loadings on the higher-order factor, indicating that a proportion of the variance in each conceptual grouping of factors can be explained by a common factor. Overall, Model 2 displayed a good fit to the data, with most indexes either approaching or exceeding the recommended cutoff values (e.g., Comparative fit index (CFI) > .90; Root mean squared error of approximation (RMSEA) < .03).

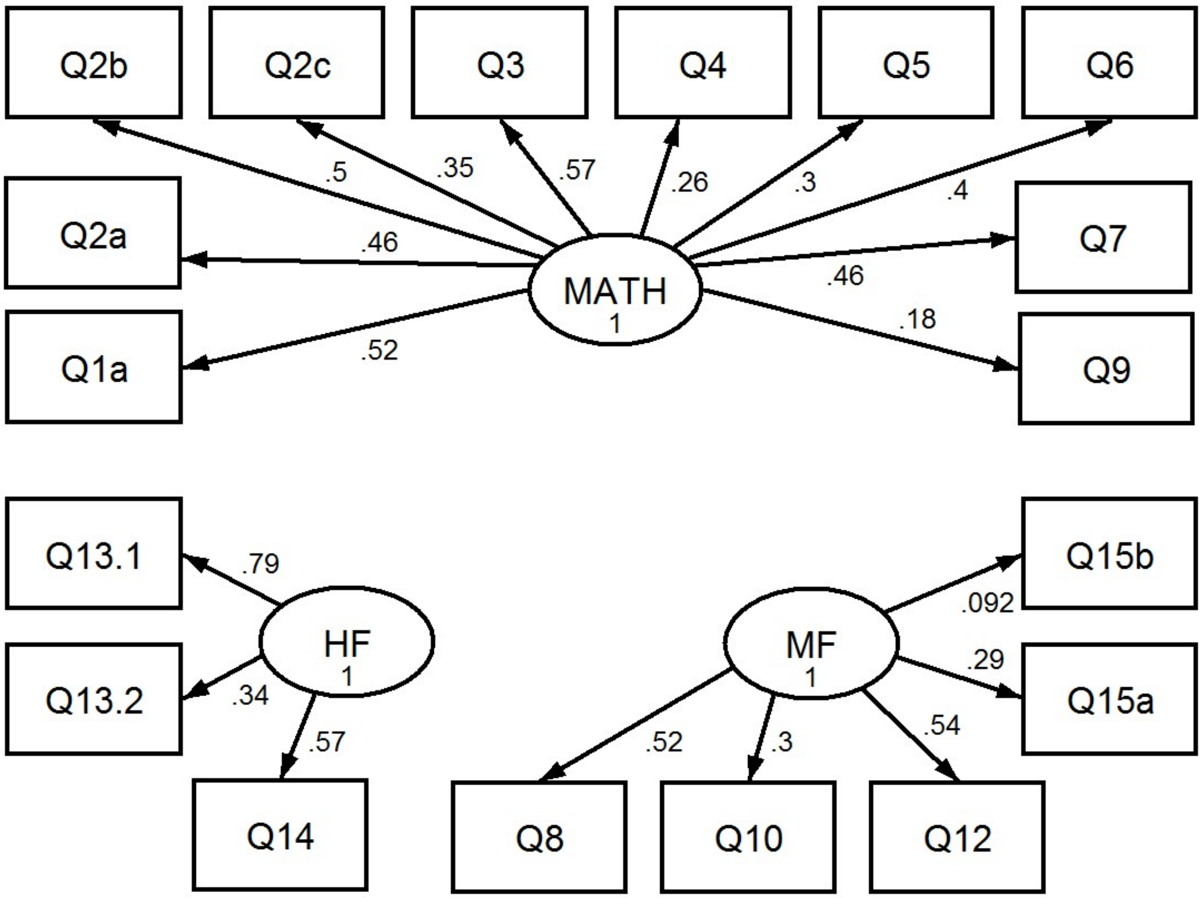

**Figure 5.7 Path diagram for the Model 1 with factor loadings (standardized regression weights)**

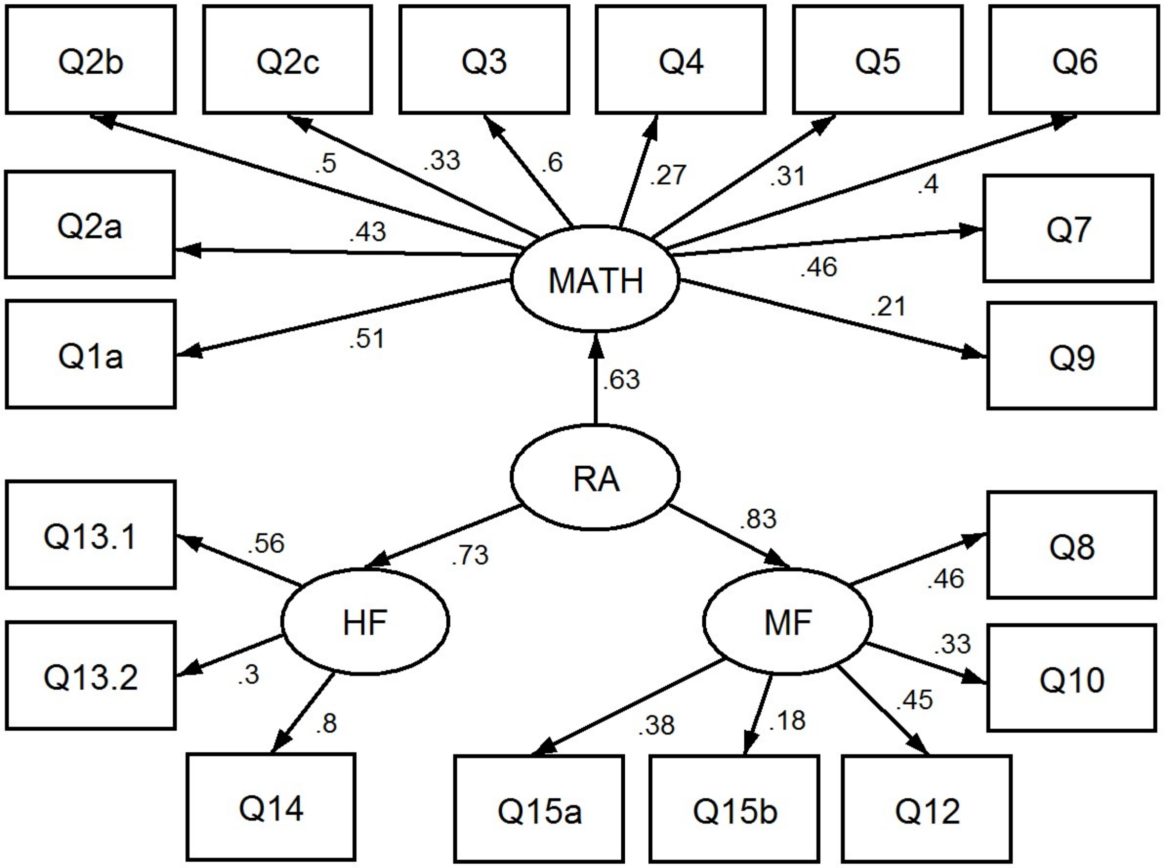

**Figure 5.8 Path diagram for the Model 2 with factor loadings (standardized regression weights)**

**Table 5.9 Fit index for confirmatory factor analysis models**

| | | Model | | | |
|---|---|---|---|---|---|
| **Fit statistic** | **Recommended Value** | **1** | **2** | **3** | **4** |
| **Likelihood ratio** | | | | | |
| Degrees of freedom | n/a | 135 | 132 | 132 | 101 |
| Chi-square (model vs baseline) | Low relative to df | 247.2** | 171.7* | 165.1* | 124.8 |
| **Population error** | | | | | |
| Root mean squared error of approximation (RMSEA) | <0.03 | 0.052 | 0.031 | 0.029 | 0.028 |
| Probability RMSEA <= 0.05 | High | 0.351 | 0.995 | 0.998 | 0.995 |
| Standardized root mean squared residual (SRMR) | Small | 0.090 | 0.051 | 0.049 | 0.047 |
| **Information criteria** | | | | | |
| Akaike's information criterion (AIC) | Lower values | 6458 | 6388 | 6382 | 5551 |
| **Baseline comparison** | | | | | |
| Comparative fit index (CFI) | > 0.9 | 0.769 | 0.918 | 0.932 | 0.947 |
| Tucker-Lewis index (TLI) | > 0.9 | 0.738 | 0.905 | 0.921 | 0.937 |

*Note: *=significant at p=0.05, **=significant at p=0.01*

Models 3 and 4 also display overall good fit to the data, with most indexes showing marginally better values than Model 2. The differences between Models 2 and 3 align with the exploratory factor results that pointed to possible issues of construct underrepresentation in the Mass Flow and Heat Flow categories. However, because the fit statistics for Models 3 and 4 show only marginal improvements, additional studies will need to be conducted to define the conceptual understanding that are currently categorized as Mass Flow and Heat Flow, and to determine if additional question items should be removed from the Mathematics category.

## 5.6 Limitations and Future Work

Douglas and Purzar (2015) discuss the ongoing developmental nature of assessment tools such as concept inventories, suggesting that establishing a tool's validity is never quite over. While many of the results presented in this paper point to an average level of validity for this version of the RACI, there are several research steps that may improve its diagnostic abilities. Because some results pointed to possible construct underrepresentation in the physical science context categories, additional research should focus on the cognitive and observation corners of the RACI. This can be achieved through additional observations of student learning coupled with interviews to examine how students solve particular problems. Another approach to increasing the overall validity for the RACI would be to conduct a Delphi study, which is a structured process for collecting and distilling knowledge from a group of experts that has been used in the development of several concept inventories (Goldman et al., 2008; Linstone et al., 1975; Streveler et al., 2003).

A common goal for some concept inventories is the diagnosis a student's propensity for misconceptions or common errors using patterns of distractor response patterns (Jorion et al., 2015). Diagnostic classification modeling or a combination of item response theory and diagnostic classification models can be used to assess student misconceptions (Bradshaw and Templin, 2014; Jorion et al., 2015). While this stage of the RACI development did not include the aim of diagnosing misconceptions, future work should include the development of a Q-matrix (a binary representation of cognitive attributes associated with each answer choice) for existing question items, and plans to develop addition items that will assist in the diagnosis of particular misconceptions.

The conclusions drawn from administrations of the RACI also have certain limitations that should be acknowledged. While statistical measures supported the sample size of this study for the tests conducted in this paper, the samples of students in the RACI pilot tests have thus far been generally small. Also, convenience samples were used rather than random samples. While efforts were made to collect results from students enrolled in different courses at different universities, some of these findings may be unique to particular populations of students. Because the pre-course sample of this pilot test population was much smaller than the post-course sample, the pre-course analysis was excluded from this paper. As much of the usefulness of concept inventories lies in formative pre-course assessments, future stages of this study should seek to include larger, random samples of pre-course and post-course populations across various institutions and disciplines. As new versions of the RACI are developed that further establish its reliability and validity, pre-course and post-course findings may aid in the development of instructional techniques designed to address particular student misconceptions.

## 5.7 Conclusions

We developed the RACI over several iterative developmental stages in order to assess students' conceptual understanding of rate and accumulation processes. Psychometric tests were performed to assess the reliability and validity of the RACI. The Cronbach's alpha provided evidence of an average level of reliability for the overall test and mathematics category, and poor reliability for the mass flow and heat flow categories. Item testing analysis suggested the removal of two question items from the instrument. Structural equation modeling provided evidence that most of the remaining items mapped to the three contextual categories defined in our cognitive model, and that a higher order factor of rate and accumulation understanding explains the shared variance of the context categories. Issues of potential construct underrepresentation were uncovered in two of the context categories. Additional research stages for RACI development should focus on modeling student cognition and learning, and developing additional question items that align with the cognitive model.

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# Appendix A5

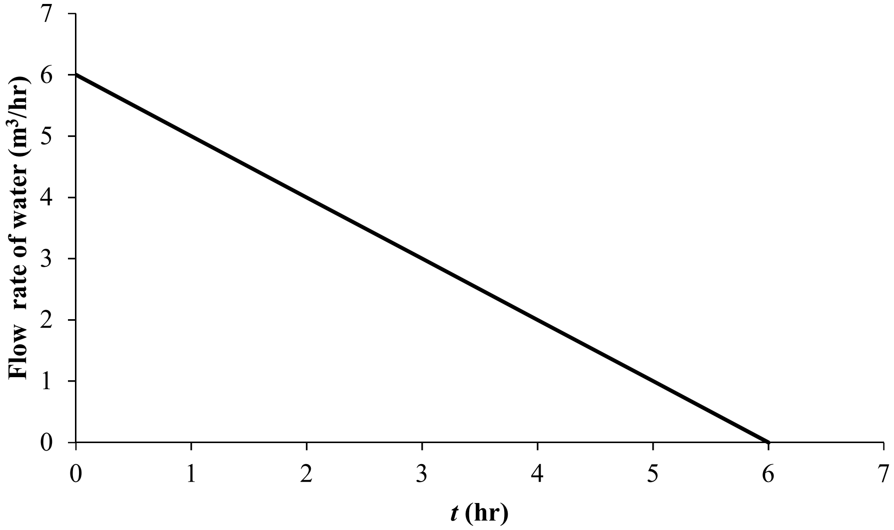
**Table A5.1 Categorical judgment scheme for concept inventory evaluation (adapted from Jorion et. al, 2015)**

| Analysis | Excellent | Good | Average | Poor | Unacceptable |
|---|---|---|---|---|---|
| **Classical test theory** | | | | | |
| **Item Statistics** | | | | | |
| Difficulty | 0.2 to 0.8 | 0.2 to 0.8 (3) | 0.1 to 0.9 | 0.1 to 0.9 (3) | 0.0 to 1.0 |
| Discrimination | > 0.2 | > 0.1 | > 0.0 | > -0.2 | > -1.0 |
| Total score reliability | | | | | |
| Cronbach's alpha of total score | > 0.9 | > 0.8 | > 0.65 | > 0.5 | > 0.0 |
| Cronbach's alpha-with-item-deleted | All items less than overall α | (3) | (6) | (9) | > (9) |
| **Item response theory** | | | | | |
| Individual item measures | | | | | |
| All items fit the model | (2) | (4) | (6) | (8) | (10) |
| **Structural analyses** | | | | | |
| Exploratory factor analysis | Conforms to pre-directed constructs | (5) | (10) | (15) | > (15) |
| **Confirmatory factor analysis** | | | | | |
| Item loading | > 0.3 | > 0.3 (3) | > 0.1 | > 0.1 (3) | > -1.0 |
| Comparative fit index | > 0.9 | > 0.8 | > 0.7 | > -0.6 | > 0.0 |
| Root-mean-square error approximation | < 0.03 | < 0.05 | < 0.10 | < 0.20 | > 0.20 |

*Note: Cell values in parenthesis indicate the number of items that can fall outside of this recommendation*

## RACI 2.0 Question Items

1. **A reservoir is filled with a single inflow pipe. The reservoir is empty when the inflow pipe is opened at *t* = 0. The flow rate of water into the reservoir (in $m^3$/hr) with respect to time, *t*, is shown below.**



**a. How much water flows into the reservoir in the first 2 hours?**

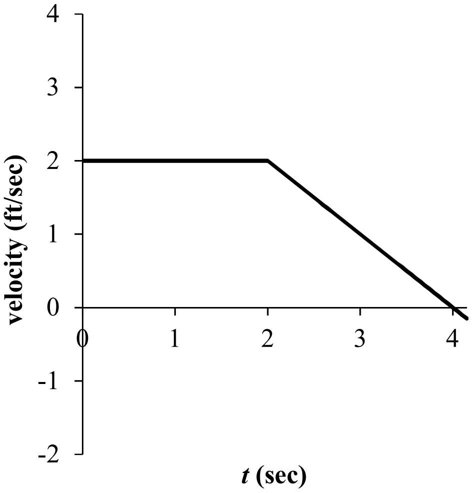
a. 1 $m^3$
b. 2 $m^3$
c. 4 $m^3$
d. 9 $m^3$
e. 10 $m^3$
f. 16 $m^3$

**b. What is the flow rate of water into the reservoir at hour 4?**

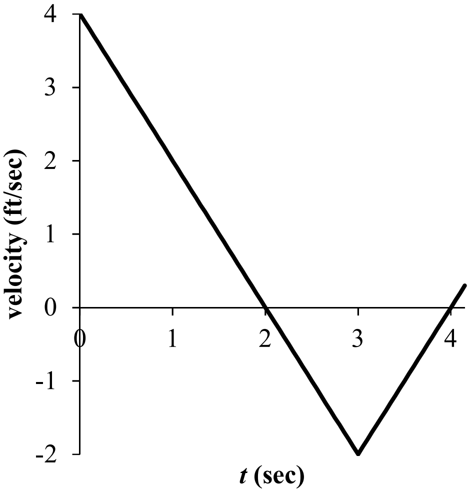
a. 1 $m^3$/hr
b. 2 $m^3$/hr
c. 4 $m^3$/hr
d. 9 $m^3$/hr
e. 10 $m^3$/hr
f. 16 $m^3$/hr

**2. The figures below show velocity functions with respect to time, *t*, for two people walking along two straight paths.**

**Person A:**



**Person B:**



**a. Which person is further from their starting position at *t* = 4?**

a. Person A
b. Person B
c. Both are the same distance from their respective starting point

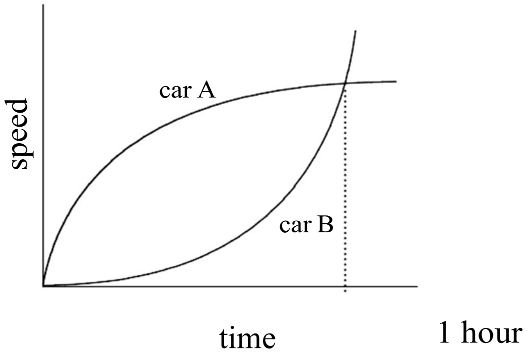
**b. Which person travels a greater total distance over the time interval *t* = 0 to *t* = 4?**

a. Person A
b. Person B
c. Both travel the same total distance

**c. Which person has a greater acceleration at *t* = 4?**

a. Person A
b. Person B
c. Both have the same acceleration at this time

**3. The given graph represents speed vs. time for two cars. (Assume the cars start from the same position and are traveling in the same direction.) Use this information and the graph below to answer item a.**



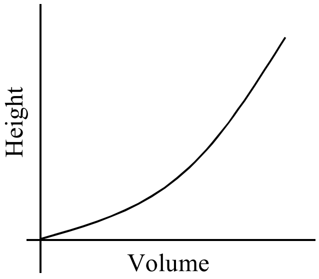
**a. What is the relationship between the *position* of car A and car B at $t = 1$ hr.?**

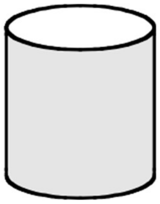
a. Car A and car B are colliding.
b. Car A is ahead of car B.
c. Car B is ahead of car A.
d. Car B is passing car A.
e. The cars are at the same position.

**4. The distance, *s* (in feet), traveled by a car moving in a straight line is given by the function, $s(t) = t^2 + t$, where t is measured in seconds. Find the average velocity for the time period from $t = 1$ to $t = 4$.**

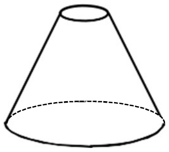
a. $5\,{}^{ft}/_{\text{sec}}$
b. $6\,{}^{ft}/_{\text{sec}}$
c. $9\,{}^{ft}/_{\text{sec}}$
d. $10\,{}^{ft}/_{\text{sec}}$
e. $11\,{}^{ft}/_{\text{sec}}$

**5. The following graph represents the height of water as a function of volume as water is poured into a container. Which container is represented by this graph?**

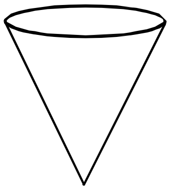




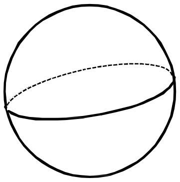
__a__



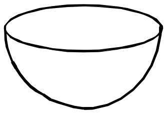
__b__



__c__



__d__



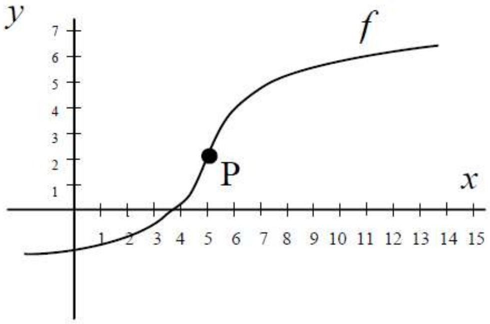
__e__

6. **A baseball card increases in value according to the function, $b(t) = \frac{5}{2}\,t + 100$, where *b* gives the value of the card in dollars and *t* is the time (in years) since the card was purchased. Which of the following describe what $\frac{5}{2}$ conveys about the situation?**

I. The card's value increases by $5 every two years.
II. Every year the card's value is 2.5 times greater than the previous year.
III. The card's value increases by $\frac{5}{2}$ dollars every year.

a. I only
b. II only
c. III only
d. I and III only
e. I, II and III

7. **Using the graph below, explain the behavior of function *f* on the interval from $x = 5$ to $x = 12$.**



a. Increasing at an increasing rate.
b. Increasing at a decreasing rate.
c. Increasing at a constant rate.
d. Decreasing at a decreasing rate.
e. Decreasing at an increasing rate.

8. **Two bathtubs are partially filled with water and have identical outlet drains which are plugged. The width and height of the bathtubs are equal, but the length of Bathtub 1 is twice that of Bathtub 2. The water level in both bathtubs is equal and no water is entering either bathtub.**

   a. **If the outlet drains of each bathtub are unplugged at the same time, how will the water flow rates of the outlet drains compare?**

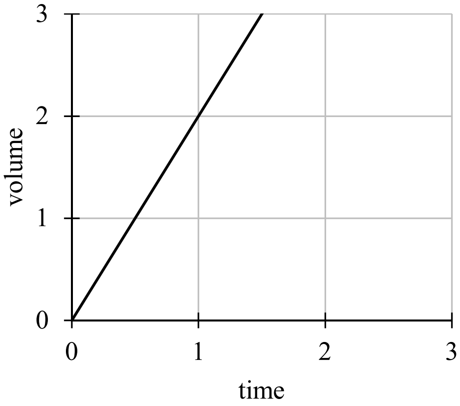
      a. Outlet water flow rate in Bathtub 1 is greater than that of Bathtub 2
      b. Outlet water flow rate in Bathtub 1 is less than that of Bathtub 2
      c. Outlet water flow rate in Bathtubs are equal

   b. **Because…**

      I. Flow rates will depend on the surface area of water in the tubs
      II. Flow rates will depend on the height of water in the tubs
      III. Flow rates will depend on the size of the drains

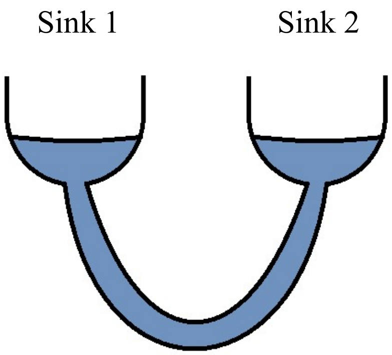
   a. I only
   b. II only
   c. III only
   d. I and II only
   e. I and III only
   f. II and II only
   g. I, II and III

**9. A hose is used to fill an empty wading pool. The graph shows volume (in gallons) in the pool as a function of time (in minutes). Which of the following defines a formula for computing time, *t*, as a function of the volume, *v*?**



a. $v(t) = \frac{t}{2}$
b. $t(v) = 2v$
c. $t(v) = \frac{v}{2}$
d. $v(t) = 2t$
e. None of the above

**10. Two identical sinks are connected with a single pipe as shown. Both sinks are partially filled with water. The sinks are fixed at the same height.**



**a. Additional water is added to Sink 1 by pouring water from a pitcher. As the water is being added to Sink 1, the water level in Sink 2 will be:**

a. Rising
b. Falling
c. Remaining the same
d. Unknown (not enough information to select one of these three answers)

**11. A gardener has two identical planter boxes that are filled with different mixtures of potting soil. The first box contains soil with 50% porosity (or void space) and the second box contains soil with 40% porosity. Both planters are completely dry, so the gardener uses two hoses with equal constant water flow rates to water both planters simultaneously.**

**a. Which of the planters will collect water at a faster rate?**

a. Planter 1 will collect water at a faster rate.
b. Planter 2 will collect water at a faster rate.
c. Both systems will collect water at the same rate.
d. Unknown (not enough information to select one of these three answers)

12. **Two identical graduated cylinders with identical spigots at the bottom are partially filled with water. The water level in Graduated Cylinder 1 (GC1) is twice that of Graduated Cylinder 2 (GC2).**

    a. **If the spigots of each graduated cylinder are opened fully at the same time, how will the water flow rates of the spigots compare?**

        a. Spigot water flow of GC1 will be greater than that of GC 2
        b. Spigot water flow of GC1 will be less than that of GC 2
        c. Spigot water flows are equal

    b. **Because…**

        a. Additional water will result in slower flow rate out of the spigot
        b. The water flow rates are proportional only to the size of the cylinders and spigots
        c. A higher water level will create more pressure on the water which will increase the water flow rate
        d. Equal gravitational forces acting on the water in each cylinder will create equal water flow rates

13. **You would like to melt ice which is at 0°C using hot blocks of metal as an energy source. One option is to use <u>one</u> metal block at a temperature of 200°C and a second option is to use <u>two</u> metal blocks each at a temperature of 100°C. Each individual metal block is made from the same material and has the same mass and surface area. Assume that the heat capacity is not a function of temperature.**

    a. **If the blocks are placed in identical insulated containers filled with ice water, which option will ultimately melt more ice?**

        a. Either option will melt the same amount of ice.
        b. The two 100°C blocks
        c. The one 200°C block.

**b. Because…**

a. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used.
b. Using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer.
c. The amount of energy transferred is proportional to the mass of blocks and the change in block temperature during the process.
d. The temperature of the hotter block will decrease faster as energy is transferred to the ice water.

**c. Which option will melt ice more quickly?**

a. Either option will melt ice at the same rate.
b. The two 100°C blocks.
c. The one 200°C block.

**d. Because…**

a. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used.
b. The higher temperature block creates a larger temperature gradient which will increase the rate of energy transfer.
c. The temperature of the hotter block will decrease faster as energy is transferred to the ice water.
d. The rate of heat transfer is proportional to the surface area of blocks and the temperature difference between the blocks and ice.

**14. You have a glass of tea in a well-insulated cup that you would like to cool off before drinking. You also have 2 ice cubes to use in the cooling process and an equivalent mass of crushed ice.**

**a. Assuming no energy is lost from the tea into the room, which form of ice (cubes or crushed ice) added to your tea will give a lower final drink temperature?**

a. The crushed ice.
b. The ice cubes.
c. Either will lower the drink temperature the same amount.

**b. Because…**

a. Energy transfer is proportional to the mass of ice used.
b. Crushed ice will melt faster and will transfer energy from the tea faster.
c. Ice cubes contain less energy per mass that crushed ice so tea will cool more.
d. Ice cubes have a higher heat capacity than crushed ice.
e. Crushed ice has more surface area so energy transfer rate will be higher.

**15. An engineering student has two beakers containing mixtures of dye in water. The first beaker has a 1% dye solution (1 gram of dye in 100 grams of water) and the second beaker has an equal volume of a 2% dye solution (2 grams of dye in 100 grams of water). The student places 2 identical sponges in the 1% dye solution and 1 sponge in the 2% dye solution.**

**a. Which of these combinations will absorb more dye?**

a. The two sponges in the 1% solution will absorb more dye.
b. The one sponge in the 2% solution will absorb more dye.
c. Both systems will absorb the same amount of dye.

**b. Which of these combinations will initially absorb dye at a faster rate?**

a. Two sponges in the 1% solution will absorb dye at a faster rate.
b. One sponge in the 2% solution will absorb dye at a faster rate.
c. Both systems will absorb dye from solution at the same rate.

# Chapter 6 Development of a case-based teaching module to improve student understanding of stakeholder engagement processes within engineering systems design[4]

## 6.1 Abstract

This paper introduces a case-based teaching module designed to increase student understanding of the importance of stakeholder engagement processes in the design of sustainable civil infrastructure engineering systems. A case study on past technology adoption and environmental injustices related to stormwater management plans in Onondaga County, NY, provides the basis for an active learning module on integrating stakeholder engagement in engineering design processes. The module begins with a review of relevant historical events, including community unrest when the needs of certain stakeholder groups were ignored. A simulation activity begins with students divided into groups, each representing an assigned stakeholder community. The students predict what engineering designs will most directly affect their stakeholder group and how various design solutions may impact other groups. Assessment tools are used to gauge the students' learning outcomes and perceptions of stakeholder engagement and engineering design after the module. Results from three implementations of the module demonstrate that the activities effectively increased student understanding of the complexities related to the engineering design processes, particularly stakeholder engagement activities. The module has also been shown to improve student motivation and interest in course material. These results provide insights for instructors seeking effective ways to bring stakeholder concerns into the classroom.

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[4] This chapter is adapted from a 2016 paper published in *New Developments in Engineering Education for Sustainable Development*

## 6.2 Introduction

Engineers are now being tasked with understanding the broader social, economic, and environmental implications of their work (Allenby et al., 2009). This presents a need for educational approaches that can enable future engineers to think holistically and incorporate a complexity of new constraints in practice (Davidson et al., 2007). It is unrealistic to expect students with little “real-world” experience to understand these complexities through traditional instructional methods. Instead, introducing pedagogical elements such as historical context, decision-making, and ethics into the classroom can aid in the development of “post-conventional” engineers. This term has been used to describe engineers who have a sense of autonomy in their work and see and treat engineering work as requiring complex decision making and social responsibility (Nair, 1997).

This paper proposes that case-based teaching modules that include simulation activities can better prepare engineering students to appreciate the complex situations they will encounter on the job. For this study, a stakeholder engagement simulation exercise on selecting management practices for stormwater management was developed to help civil and environmental engineering students learn to apply sustainability concepts and principles. The module makes use of active and collaborative teaching pedagogies within a learning cycle framework.

## 6.3 Context and Motivation for Module Development

The module was originally designed for the course *Sustainability in Civil and Environmental Systems*, a sophomore core course for Civil and Environmental Engineering majors at Syracuse University. The course encompasses a broad range of topics integrating sustainability into a traditional introductory environmental engineering course with the following primary instructional objectives:

A. Introduce principles of sustainability and systems as applied to the natural and built environments;

B. Provide skills necessary for quantitative assessments of civil and environmental engineering problems;

C. Use principles developed in class to evaluate and solve complex open-ended environmental problems and communicate the results of the analysis.

The course material is primarily covered in lectures, or a combination of lecture and in-class problem solving activities. The course is divided into four topic areas: population, energy, water, and air. Within the water unit, topics include water contaminants, physical properties of water and the hydrologic cycle, municipal water and wastewater, and urban water management including sustainable approaches for controlling urban stormwater runoff.

## 6.4 Theoretical Background

Active learning methods have consistently shown an increase in student performance in undergraduate courses in science, technology, engineering, and mathematics disciplines (Freeman et al., 2014; Prince and Felder 2006; Prince 2004). Several researchers have suggested that active learning methods may be especially useful in allowing students to better understand sustainability principles (Huntzinger et al., 2007; Korkmaz, 2011; Siller, 2001). The case-based urban water stakeholder simulation module designed in this study employs several pedagogies to promote active student learning.

### 6.4.1 Case-Based Learning

Inductive learning begins with a context for learning rather than fundamental theories and concepts. Inquiry-based learning is an inductive learning method based on the constructivist theory of learning that knowledge is constructed by the learner. Students assume responsibility for the learning process by engaging in experiences and experiments to solve a problem. Inductive teaching strategies provide students with opportunities to engage in experience-driven learning within collaborative learning environments (Prince and Felder, 2006).

Case-based learning is a type of inductive learning method in which students are presented with the context of a case study with complex, ill-defined problems to consider. Case-based learning goes beyond the constructivist theory of learning in that it defines a model of cognition that can be turned to for advice and for predictions that can be simulated to test ideas, thus allowing students to draw productive lessons from a case and transfer their knowledge to future situations (Jonassen and Land, 1999). Case-based methods have also been shown to be a preferred inductive learning style among instructors and students (Srinivasan et al., 2007).

To design case-based modules as effective inductive learning tools, the context of the case is described but the actual decisions made are withheld so students can inductively develop their own solutions to the problems presented (Lynn, 1999). The following steps to structure case-based discussions have been suggested to optimize the student learning experience in case-based environments (Kardos, 1979): (1) review of the case content, (2) statement of problems, (3) collection of relevant information, (4) development of alternatives, (5) evaluation of alternatives, (6) selection of a course of action, and (7) evaluation of solutions and review of actual case outcomes.

### 6.4.2 Learning Cycle-Based Instruction

The steps proposed for case-based learning closely follow several learning cycle models. For instance, Kolb's experiential learning theory, which asserts that experiences play a key role in the learning process, suggests that student learning occurs in two stages: *grasping experiences* (through a concrete experience phase and an abstract conceptualization phase) and *transforming experiences* (through a reflective observation phase and an active experimentation phase) (Kolb, 1984). Based on this theory, Kolb postulates that complete learning occurs when students engage in all four phases of a learning cycle, and that instructors can promote complete learning by designing course materials to encourage students to complete all learning cycle phases (Kolb et al., 2001).

## 6.5 Module Design and Implementation

The module employed in this study was designed to make use of case-based learning methods within a learning-cycle-based instructional framework. The seven steps suggested for case study design by Kardos (1979) were used in the design of the urban water stakeholder simulation module, as summarized in Table 6.1.

### 6.5.1 Case Selection and Context

Preparation for case-based learning is very demanding, as instructors must be intimately familiar with the history and current state of decisions related to the case in order to actively respond to questions during the case (Kardos, 1979). This case was selected based on the authors' expertise on sustainable urban water systems and depth of knowledge on stakeholder perspectives (Flynn et al., 2014; Flynn and Davidson, 2016). The context of the case takes place in Onondaga County, located in Central New York. Onondaga County operates a combined sewer system and must provide a control plan to manage combined sewer overflows (CSOs).

**Table 6.1 Module design components**

| Steps for Case-Based Module Development | Module Features | Pedagogy Elements |
|---|---|---|
| (1) Review of the case content | Mini lecture, videos and discussions of stormwater engineering design and Onondaga County context | Grasping experiences through concrete experience and abstract conceptualization |
| (2) Statement of problem | *As a member of a key stakeholder group in Onondaga County, what type of technologies or solutions would you consider and why?* | Case-based problem |
| (3) Collection of relevant information, and<br>(4) Development of alternatives | Stakeholder simulation activity: student group discussion aided by floating facilitators | Student collaboration; transforming experiences primarily through active experimentation |
| (5) Evaluation of alternatives, and<br>(6) Selection of a course of action | Environmental, economic, social and ethical considerations used to evaluate each set of proposals | Student collaboration; transforming experiences primarily through reflective observation |
| (7) Evaluation of solutions and review of actual case outcomes | Summary of actual changes to Onondaga County's stormwater management plans | Grasping experiences through abstract conceptualization |

Most municipal CSO control plans in the U.S. make use of traditional "gray infrastructure" solutions, or CSO control technologies that either enhance or supplement existing sewer infrastructure, which tend to be large in scale and cost. Implementing only gray infrastructure systems for urban stormwater management is neither sustainable nor sufficiently resilient to accommodate climatic changes (Novotny et al., 2010; Pyke et al., 2011). Conversely, urban stormwater systems that include green infrastructure (GI) technologies are recognized as a more sustainable management approach. Onondaga County's original CSO management plans included multiple expensive gray infrastructure technologies that were considered unjust and insufficient by many local community members. While all major regulating and regulated parties were directly involved in the Onondaga County CSO management planning process, several important stakeholder groups were not. Over time, the environmental injustices stemming from this exclusion led to the social unrest of many groups in Onondaga County, particularly the Onondaga Nation and the residents of the Southside neighborhood (Perreault et al., 2012).

### 6.5.2 Initial Module Implementation

The first implementation of the module took place in 2014 during a single lecture period lasting eighty minutes. Instruction began with grasping experiences through a mini-lecture on why stormwater engineering design is both necessary and inherently complex. Early module content also described available technology options and the stakeholders that are affected by each option. Urban stormwater management issues were reviewed and local contextualization was provided with videos of recent localized flooding on campus and the surrounding neighborhoods. The module continued with a discussion of these issues and how the framing of water issues impacts the goals, system boundaries and specific solutions. Stakeholder engagement processes were introduced and a variety of different stakeholder groups involved with and affected by municipal stormwater management decisions were discussed. Students were then presented with the context of the Onondaga County case study. Information on changes to Onondaga County's stormwater management plans to include widespread use of GI technologies were intentionally left out of the module to elicit original student ideas as the module progressed.

The case-based simulation activity was designed to promote the active experimentation phase of learning, as students explored how they would advocate for particular engineering solutions while representing a certain stakeholder group within Onondaga County, and considered what consequences would occur if their solutions were chosen. Background on the case and on each stakeholder group was presented to the students and is shown in Table 6.2. The four stakeholder groups described in Table 6.2 were selected from the multiple stakeholders involved with this case. The class was divided into four equal groups, each representing one stakeholder group. Potential solutions using gray infrastructure and GI were reviewed, as summarized in Table 6.3. Information on technology options was presented for the time period of 2007-2008, when GI technologies were acknowledged as a potential alternative to gray infrastructure technologies but not widely implemented. Students were then asked to answer the following question with their group: *As a member of a key stakeholder group in Onondaga County, what type of technologies or solutions would you consider and why?*

**Table 6.2 Stakeholder groups included in initial module**

| Stakeholder Group | Primary Interests |
|---|---|
| Onondaga County Government | Must meet consent judgment criteria to treat or mitigate 400 million gallons of annual CSO volume and decrease bacteria, phosphorus and trash loadings to Onondaga Lake using proven technologies in a cost-effective manner |
| Engineering firms | Must design proven and cost effective stormwater management solutions to meet the needs of their client (Onondaga County) |
| Southside residents | Proximity of invasive infrastructure projects, localized and basement flooding, construction disruptions, aesthetics, recreation, health |
| Onondaga Nation | Lake is a sacred site; Onondaga Nation follows a vision of environmental stewardship and cooperative resource management |

Several possible considerations were provided to the students, including economic limitations and opportunities, political and community culture, current ecosystem conditions, current state of existing infrastructure, legal constraints, and current and future climatic conditions. Students were provided time to discuss the various technology options within their groups. A floating facilitator model was employed with four instructors moving from group to group during the discussion period to respond to student questions. Each facilitator had studied different aspects of this case over multiple years and was able to provide robust answers to student questions. After the discussion, students were asked to advocate for their technology selection and to provide support based on the goals and concerns of their stakeholder group. The class ended with an open discussion of the various proposals and a brief presentation of the actual solutions implemented in Onondaga County.

**Table 6.3 Technological aspects of gray and green infrastructure**

| Technological Aspect | Gray Infrastructure | Green Infrastructure |
|---|---|---|
| Materials | Human manufactured materials | Human manufactured and natural materials |
| Benefits | Single purpose technologies for stormwater mitigation and treatment | Multifunctional technologies with multiple environmental and social benefits |
| Distribution and capacity | Large capacity to centrally treat and transport stormwater | Varied capacities to treat and manage stormwater through a diffuse network |
| System integration | Concentrates stormwater and pollutants to be treated with chemicals | Complementary to existing infrastructure; systems-thinking design |

### 6.5.3 Formative Assessment Tool

A formative assessment tool was administered directly following the module implementation to provide feedback on its effectiveness as a teaching tool. The assessment also provided information on student self-evaluations of learning outcomes, as well as their overall enjoyment of the module activities and structure. The initial formative assessment tool included a three point Likert scale (Disagree, Agree, or Strongly Agree) to assess students' perceived level of understanding on several topics after the module. Two open-ended questions were included to elicit student comments on their satisfaction of the module. Certain questions from this tool were administered during the subsequent implementations to assess if changes made to the module produced any positive effects in students' perceptions and satisfaction.

### 6.5.3 Revisions to the Module and Assessment Tools

Based on formative assessment findings from the first-year implementation (to be discussed in Section 6.6.1), several changes were made to the structure of the module. Activities were spread out over two eighty-minute lecture periods, and an innovative classroom space has also been utilized to allow for enhanced interaction of small groups within a large classroom setting. The first lecture period serves as an expansion of the mini-lecture to allow for additional discussion of stormwater management principles and possible needs of various stakeholder groups. This lecture focuses on seven stages of an engineering design process: problem definition, gathering information, generating ideas, modeling, feasibility analysis, evaluation, and decision-making. Research by Atman et. al (2007) suggests that engineering students spend significantly less time in the stages of problem definition, gathering information, generating ideas, evaluation, and decision-making stages. As these stages present opportunities for stakeholder input, the importance of stakeholder engagement throughout each of these stages is emphasized during the lecture activities.

The second period is dedicated to the simulation activity. Additional stakeholder groups (summarized in Table 6.4) were added in order to promote additional student interactions during the activity, and introduce additional complexity for students to consider during decision-making processes. An expansion of the initial formative assessment tool was developed using Bloom's Taxonomy as a framework to assess learning outcomes (Bloom et al., 1956). The revised tool is administered before and after module implementation to assess learning outcomes through student self-evaluations on fourteen question items using a five point Likert scale.

**Table 6.4 Stakeholder groups included in revised module**

| Group # | Stakeholder Group |
|---|---|
| 1 | Engineering Firm #1 |
| 2 | Engineering Firm #2 |
| 3 | Engineering Firm #3 |
| 4 | Engineering Firm #4 |
| 5 | Syracuse City Government |
| 6 | Business Owners |
| 7 | Local Environmental NGOs |
| 8 | Onondaga Nation |
| 9 | Southside Residents |
| 10 | Suburban Residents |

## 6.6 Results

Results from student evaluations of the first module implementation are presented in Table 6.5. Previous to this module implementation, urban hydrology issues were covered in several lectures with specific examples of existing technological solutions. However, stakeholder concerns and stormwater issues in Onondaga County (i.e., the Syracuse area) were not directly addressed. Following the module implementation, 95% of students agreed or strongly agreed that they had a better understanding of how course concepts apply to real world cases, and 96% felt that the module helped them to better understand urban water problems in Syracuse, NY. Anecdotal evidence suggested that most of the students in the course are not from the Central New York area and therefore would not be informed of ongoing local issues. This response is of particular importance to the instructors who encourage their students to relate course material to local contexts. Additionally, 86% of students agreed or strongly agreed that they better understood stakeholder involvement in engineering decisions following this module. This result is also notable, as increasing students' ability to understand the complexities of engineering design decisions was a primary objective of the module.

**Table 6.5 Student evaluations of 2014 module (N=30)**

| Question | Disagree | Agree | Strongly Agree |
|---|---|---|---|
| As a result of today's activities, I have a better understanding of how concepts learned in this course apply to the real world. | 5% | 75% | 20% |
| As a result of today's activities, I have a better understanding of how different stakeholders influence engineering decisions. | 14% | 59% | 27% |
| As a result of today's activities, I have a better understanding of urban water problems in the Syracuse area. | 4% | 60% | 36% |
| I enjoyed today's activities. | 25% | 57% | 18% |

Student responses to open-ended questions for three years of module implementation are summarized in Figures 6.1 and 6.2. Two instructors categorized the open comments based on common themes and language that students used to describe their experiences in the module. The first open-ended question asked what the students enjoyed most about the class activity. These comments were classified into seven groups. Many students mentioned that they enjoyed working in groups and enjoyed learning about the various interests of the different stakeholders. In comparing responses between the first year of the module implementation (2014) and the second and third implementations (i.e., after the module was modified), several trends in student preferences stand out. The largest differences are an increase in students' enjoyment stemming from "real-world" complexities and a connection to their future careers. This suggests that the revised module succeeds in expanding students' understanding of how material learned in the classroom will apply to future engineering design projects they may encounter in their careers. Many students consistently responded positively to incorporating more group interactions during class time. Several responses to this question also indicated an increase in student motivation to continue investigating stormwater engineering issues. Two such comments are included below:

> *"I thought the lecture was well done and I found it to be engaging, interesting and extremely useful. This was possibly the most useful lecture I have here at Syracuse and reminded me why I chose engineering."*
>
> *"I enjoyed how it was based off of real world problems, which made it feel a lot more realistic. It was the first time I have been involved in an activity that has shown me what I may deal with in my future profession."*

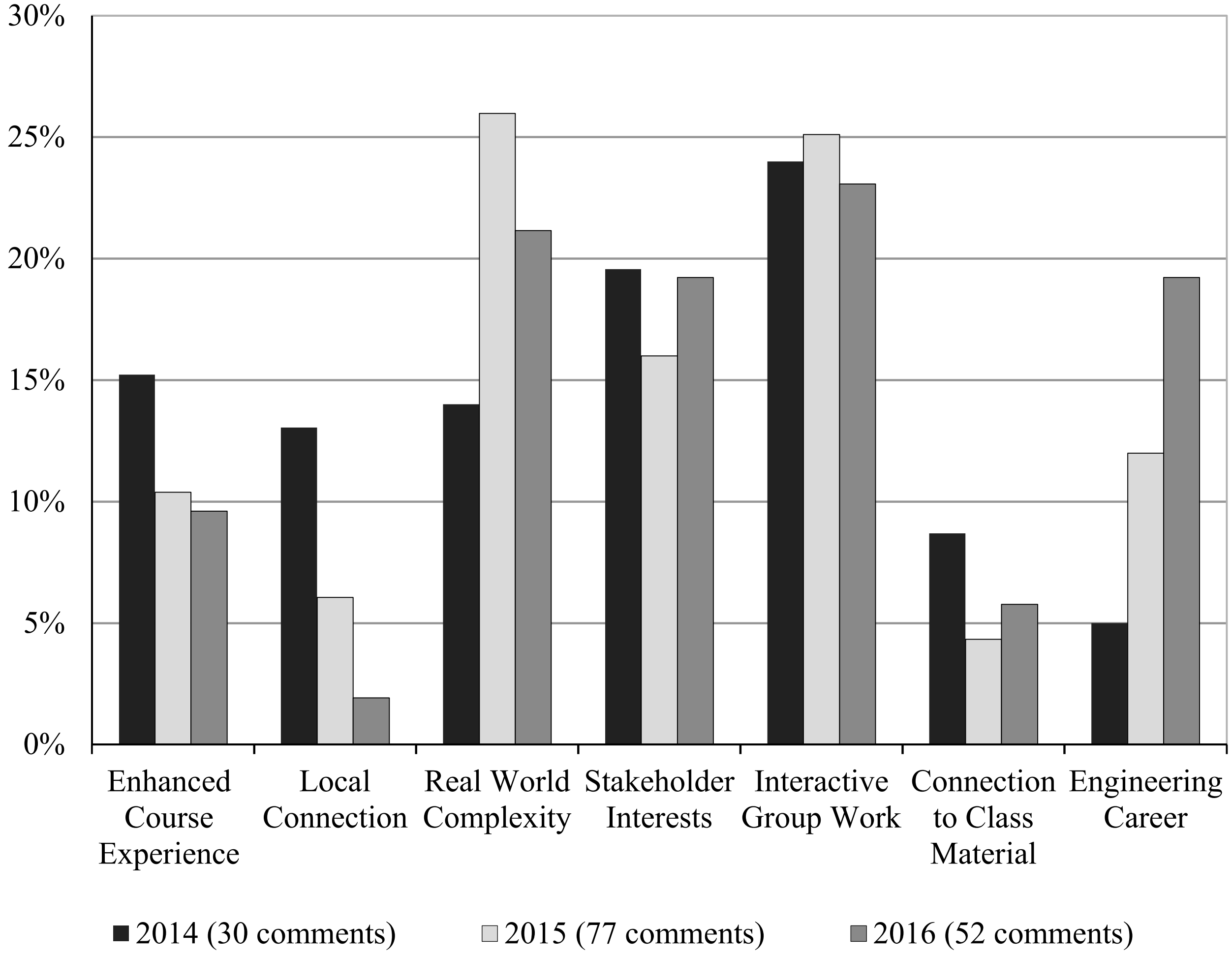

**Figure 6.1 Student responses to "*What did you enjoy most about today's activities?*"**

A second open-ended assessment question relates to improvements that can be made to the module. Responses to this question are summarized in Figure 6.2. In 2014, most comments related to group size and limited interaction within the groups, while in 2015 and 2016 the primary area of improvement identified by the students is more time to work through the simulation activity. Requests for additional information or structure within the module tend to be consistent across all years.

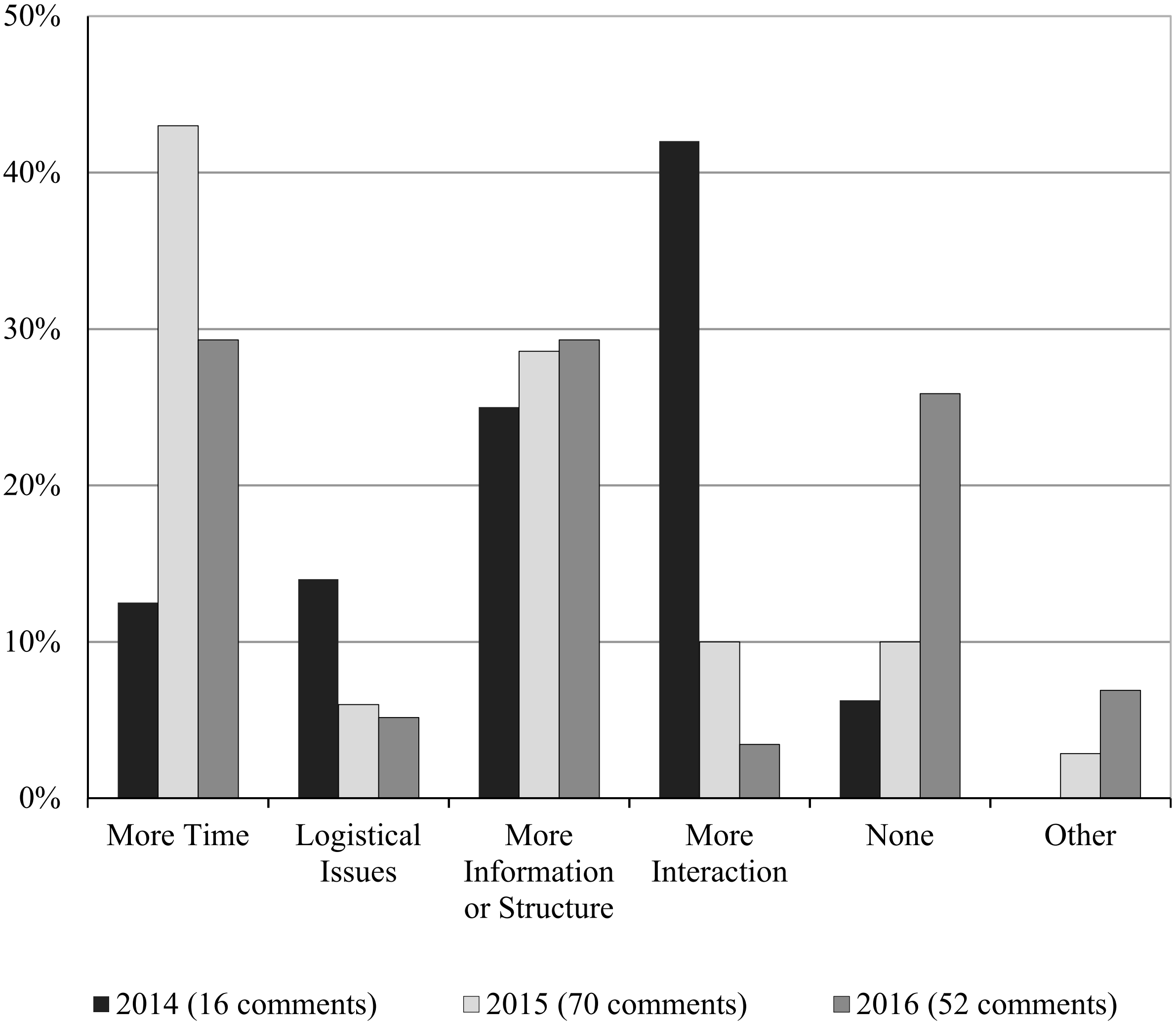

**Figure 6.2 Student responses to "*What suggestions do you have for improvement of today's activities?*"**

Results from student self-assessments of learning outcomes for 2015 and 2016 are summarized in Table 6.6. Student responses to multiple questions are averaged according to each Bloom's Taxonomy level, and a paired two sample t-test for differences in means is used to assess the significance of changes in student knowledge at each level before and after module implementation. All results for both years show significant learning gains across all taxonomy levels. Because control data is not available for equivalent learning outcomes without using the simulation activity, these results cannot precisely demonstrate the effectiveness of the case-study module against traditional classroom learning activities. However, when considered along with student responses of overall satisfaction with the module, the revised version of the module is shown able to both meet the learning outcomes of the course, particularly in regards to students' analysis of complex open-ended environmental problems, while enhancing the learning experience for students.

**Table 6.6 Student self-assessments of learning outcomes using mean values from a five point Likert scale (1=strongly disagree, 5=strongly agree)**

| Bloom's Taxonomy Level | Question | 2015 | | 2016 | |
|---|---|---|---|---|---|
| | | Pre-survey | Post-survey | Pre-survey | Post-survey |
| **Knowledge** | I can define the natural hydrologic cycle. | 3.49 | 4.16 | 3.66 | 4.08 |
| | I can define urban water management. | 3.26 | 4.14 | 3.32 | 4.08 |
| | I can define gray infrastructure. | 2.73 | 4.21 | 2.89 | 3.95 |
| | I can define green infrastructure. | 3.51 | 4.30 | 3.63 | 4.18 |
| | I can define stakeholders. | 3.41 | 4.28 | 3.55 | 4.18 |
| | *Mean "Knowledge" value* | 3.28 | 4.22*** | 3.41 | 4.09*** |
| **Comprehension** | I can give examples of stakeholders in urban water management systems. | 2.82 | 4.22 | 3.02 | 4.13 |
| | I can explain the difference between urban and natural hydrology. | 3.09 | 4.1 | 3.16 | 3.89 |
| | I can explain urban water issues. | 3.44 | 4.16 | 3.55 | 4.15 |
| | I can explain urban water issues in Syracuse. | 3.13 | 4.26 | 3.19 | 4.08 |
| | I can explain the differences between gray and green infrastructure. | 2.73 | 4.20 | 2.92 | 3.93 |
| | *Mean "Comprehension" value* | 3.04 | 4.19*** | 3.17 | 4.04*** |
| **Application** | I can apply hydrologic principles to urban water system. | 2.71 | 3.88*** | 2.95 | 3.77*** |
| **Analysis** | I can prioritize diverse stakeholder needs within engineering decisions. | 2.69 | 4.04*** | 2.98 | 3.92*** |
| **Evaluation** | I can evaluate water infrastructure options, such as gray vs. green infrastructure, within and urban water management system. | 2.56 | 3.98 | 2.90 | 3.93 |
| | I can critique past and present urban water management decisions in Syracuse. | 2.79 | 4.04 | 2.90 | 4.15 |
| | *Mean "Evaluation" value* | 2.68 | 4.01*** | 2.90 | 4.04*** |

***p<0.01 for paired two sample t-test significance for mean value in each Bloom's Taxonomy level

## 6.7 Conclusions and Future Work

To encourage active student engagement in learning about sustainable urban stormwater system design, a case-based module was developed and implemented in a sophomore civil and environmental engineering course. Assessment results suggest that the module effectively increased student understanding of complex decision making processes required of engineers. The instructors observed high levels of student involvement and engagement in the material throughout the module, particularly during the simulation activity. Students enjoyed the collaborative learning activities and focus on a local engineering case study involving diverse stakeholder concerns.

Several modifications were applied after initial module implementation in response to student suggestions, such as the addition of multiple stakeholder groups and activities during the stakeholder engagement simulation. Several student comments from the first-year implementation also suggested the need for additional reflective observation time. Learning activities are now designed as a two-day module, with one full lecture period dedicated to simulation activities. An innovative classroom space has also been utilized to allow for enhanced interaction of small groups within a large classroom setting. Additional work on this module aims to further engage students with local, real-world situations that foster an understanding of the complexities of inclusive, human-centered design processes.

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# Chapter 7 Conclusions

This research has the potential to inform current decision-makers on influential factors related to the design and implementation of sustainable civil infrastructure systems, and guide best practices in education that will influence future engineers' understanding of sustainable systems design principles. From a policy innovation perspective, this research contributes to a deeper understanding of sustainable infrastructure adoption as both an environmental outcome-based and community-interest driven process. From a pedagogical perspective, this work reveals a need for engineering faculty to both develop strategies that can address student misconceptions related to rate and accumulation problems and provide opportunities to actively engage in learning complex engineering design concepts.

## 7.1 Summary of Findings

In the first study of this thesis, described in Chapter 2, I developed a social-ecological framework for categorizing factors that condition the adoption of GI programs by stormwater management authorities. While it has been argued that there is no need to create a separate technological domain in the social-ecological framework (McGinnis and Ostrom 2014), this study demonstrates a need to more fully develop robust descriptions of technological attributes within an urban stormwater system, particularly for technology decision-making activities. This framework can provide guidance for officials and professionals in the development of more sustainable stormwater management planning methods. This research may also provide insight for other sustainable technology decision-making frameworks.

The second study of this thesis, described in Chapter 3, describes a case study that analyzes the evolution of stormwater management plans in Onondaga County, NY, from 1998 to

2009. Interviews with stakeholders and document analysis were used to identify important factors that led stormwater management authorities to overhaul existing CSO management plans by adopting a comprehensive GI program to replace certain gray projects. Findings suggest that the adoption of this program can be understood as an alignment of several sociopolitical factors, including the presence of a policy entrepreneurship coalition in support of alternative stormwater management plans, the election of a key political official who acknowledged the needs of local stakeholders, and a shift in mindset of local and national officials as to what technologies are effective for stormwater management. These findings demonstrate the importance of integrating diverse stakeholder goals and adaptive decision making to address urban stormwater management challenges.

In the study described in Chapter 4, I developed an empirical model of GI program adoption decisions in large U.S. communities with combined sewer systems. A sewer management authority's decision to adopt a large-scale GI program is modeled as a two-tier decision to separately assess factors that influence the decision to adopt a program, and factors that influence decisions related to the extent of planned program implementation. I find that the decision to adopt a large-scale municipal GI program is largely driven by the population size of a municipality and precipitation characteristics, while the extent of program implementation is also driven by socioeconomic characteristics of municipal residents in addition to the total amount of remaining capital infrastructure needs for CSO compliance. By examining the motivation for and barriers to green infrastructure adoption, this research has important implications for environmental governance at the municipal level.

Knowing how students think and learn about rate and accumulation processes in complex systems can help educators better prepare students for their engineering careers. This work provides educators with a reliable and valid assessment tool that can be used to identify gaps in student understanding of rate and accumulation processes. The study described in Chapter 5 provides evidence of validity and reliability of the RACI through structural equation modeling and multidimensional item response theory. Validity and reliability evidence indicates that the RACI can be used to measure students' overall understanding of all concepts identified. Factor analysis findings point to issues of possible construct underrepresentation in certain subscales of conceptual understanding; thus, evidence for the validity of RACI subscales is limited.

This research also provides educators with findings on incorporating broad, complex constraints such as stakeholder needs into undergraduate engineering coursework. The study discussed in Chapter 6 describes the development and use of a case-based learning module for use in a sophomore civil and environmental engineering class. Findings from Chapter 2 of this dissertation are used to develop a case-based teaching module on incorporating stakeholder engagement processes in engineering system design. This study demonstrates the overall success of using a simulation activity to engage students in complex engineering decision-making scenarios. Thus far, each implementation of the module has been shown to enhance student understanding of stakeholder engagement principles, as well as overall satisfaction with course material. While the module presented in this thesis can be incorporated in other engineering courses, the success of a case study module may be determined in part by an educator's level of expertise on the case materials. Preparation for case-based learning can be quite demanding, and instructors should be very familiar with the history and current state of the case to provide nuanced responses to student questions. This should be viewed as a worthy task, as exposure to open-ended, real-world scenarios can help engineering students appreciate the complex design considerations that will be required of them in their careers.

## 7.2 References

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