Blue-Green Systems

Blue-Green Systems Vol 3 No 1, 62 doi: 10.2166/bgs.2021.015

How can we govern large-scale green infrastructure for multiple water security benefits?

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ABSTRACT

Traditional, limited purpose grey infrastructure has failed to address the world's interrelated water challenges. Improving water security will increasingly require more integrated responses. This paper examines large-scale green infrastructure (LSGI), planned natural or hybrid systems that materially affect water security at the watershed scale, as one such response. This paper examines key challenges for governing and financing LSGI, which hinder its broader use. We report on four case studies located in the United States where LSGI is being employed to improve water security. Through analysis of these case studies and related literature, we identify three themes important for LSGI governance: cost sharing, performance monitoring, and legitimization. First, we hypothesize that formal cost sharing based on the multiple benefits LSGI provides could enable wider adoption, but find that in these examples cost sharing is limited and informal. Second, our research suggests that expanding performance monitoring to encompass key secondary benefits could help clarify how the benefits and burdens of a project are distributed across stakeholders, facilitate cost sharing, and enhance project legitimacy. Finally, LSGI will require further legitimization – developing a broader perception that LSGI is an appropriate alternative or complement to grey infrastructure – to develop as a viable contributor to water security.

Key words: environmental governance, green infrastructure, grey infrastructure, sustainable development, water management, water security

HIGHLIGHTS

- Large-scale green infrastructure (LSGI) has promise to address complex water security challenges.
- LSGI represents a paradigm shift from traditional grey infrastructure.
- Case studies suggest that governance of LSGI lacks maturity, gating wider adoption and diffusion.
- Novel funding models, improved performance monitoring, and legitimization at multiple scales must be addressed to increase the adoption and diffusion of LSGI.

INTRODUCTION

There is an acute and well-recognized need for water resource management that meets human and ecosystem needs while being resilient to changes in climate, land use, and population. Traditional approaches to water management have predominantly employed 'grey infrastructure' with narrow sets of functions, such as treatment plants, pipelines, and reservoirs. Due in part to the historical reasons for its development, grey infrastructure has often been geared to address a single element of water resource management divorced from broader context, such as drinking water supply or wastewater treatment (Sedlak 2014), or operated to meet a few, sometimes competing, purposes, such as reservoirs used for flood control and water supply. While this approach had profound public health benefits in the past, it has also generated severe externalities, including damage to ecosystem function and inequitable distribution of costs and benefits among human communities (Gleick 2003).

The concept of water security nests water-related services within their broader societal and environmental context (Water 2013), putting good governance at the center of integrative approaches to water management (Cook & Bakker 2012). Water security involves ensuring reliable provision of water services with greater resilience to emerging risks (Butler *et al.* 2017). Resilience, for the purposes of this paper, includes traditional notions of the ability of engineering and biophysical infrastructure to recover from shocks, but also resilient water governance (Rodina 2019) and the need for socio-ecological systems to provide a persistent set of functions while adapting to changing conditions (Plummer & Baird 2021). Attaining water security goals thus requires achieving a broad suite of benefits and managing a wide range of risks. Working towards multiple goals in this way could be accomplished either by complex portfolios of limited-purpose projects or by a shift toward integrated solutions that simultaneously address multiple elements of human and environmental well-being. Increasing integration poses new governance challenges as traditionally siloed institutions are not well equipped to implement multi-benefit approaches that cross customary jurisdictional boundaries. Thus, achieving a holistic vision for water security implies the need for more integrated governance.

Water security is scale-dependent. At the international and country level, efforts to achieve water security involve water diplomacy and transnational politics (Conca 2006) and countries are denominated as 'water secure' (Vorosmarty *et al.* 2010) based on their overall success at tackling water issues. International and national efforts, however, are often difficult to disaggregate and address water security challenges on the ground. To be relevant to the physical and institutional realities of water, water security must be implemented at regional, local, urban (Nazemi & Madani 2018) and community scales (Dickson *et al.* 2016; Shrestha *et al.* 2018). In this paper, we examine case studies of one approach to implementing water security in a more holistic way: large-scale green infrastructure (LSGI), a multifunctional, multi-benefit alternative to grey infrastructure. While the use and governance of small-scale green infrastructures to achieve water security at the community and urban level has received increasing attention (Dietz 2007; Ahiablame *et al.* 2013; Jia *et al.* 2016) there have been few studies on governance of LSGI to promote water security at the watershed level. Accordingly, this paper addresses challenges associated with governing LSGI using traditional models developed for limited-purpose approaches to water management. Individual LSGI projects will often become the provenance of multiple governing entities, each of which is structured to operate independently. This combination presents opportunities for collaboration, and corresponding challenges that emerge from the need for coordination.

The paper proceeds as follows: First, we describe a conceptual framework for discussing water security, LSGI, and environmental governance. Second, we introduce the methods employed in this study. Third, we summarize our four case studies. Finally, we discuss our results and the themes of cost sharing, performance monitoring, and legitimization, and conclude with implications from the research.

We hypothesize that multi-benefit projects present opportunities for joint funding and financing arrangements by multiple beneficiaries, where costs could be distributed among cooperating entities using existing valuation methods. However, implementing such arrangements seems difficult in practice, particularly using traditional financing vehicles. We argue that performance monitoring is a key requirement for generating clarity among parties for cost sharing. Agreeing on joint funding is difficult given uncertainty about the benefits and costs of new technologies. Increasing confidence in the nature and magnitude of a project's benefits, and how they align with the interests of each party, through well-targeted performance monitoring may be helpful. Broader legitimization of LSGI among water and environmental managers, financiers, and others would enable wider diffusion and adoption.

CONCEPTUAL FRAMEWORK

Water security and LSGI: multiplicity of solutions for multiplicity of challenges

The concept of water security has evolved from referencing particular threats to human security to reflecting multiple interconnected water management challenges and risks. In the literature there is no consensus on the breadth and scope of water security (Cook & Bakker 2012), but there is an overall understanding that championing water security will require multi-dimensional and multiscale solutions. Water security is increasingly understood to transcend water provision and include resilience to a range of water related challenges (Butler *et al.* 2017) such as ensuring water quality and human well-being, protecting ecosystems and livelihoods, reducing water pollution, and reducing risk of water related disasters (Grey & Sadoff 2007; UNWater 2013; Sadoff *et al.* 2020).

Although these and other dimensions of water security are often managed separately, they are in reality inextricably related and interdependent (van Beek & Lincklaen Arriens 2014, p. 15). Moving from current siloed governance towards more multifaceted water resource management and infrastructure approaches will be necessary (Lenton & Muller 2012) to achieve a broad suite of benefits implied by the water security paradigm, and to manage the concomitant range of risks.

Even though there are no 'one-size-fits-all' solutions to increasing water security, and appropriate measures will depend on local conditions (van Beek & Lincklaen Arriens 2014), green infrastructure (GI) holds promise to become one of those solutions, being able to simultaneously address several water security challenges. GI is a water management approach that uses the hydrological and ecological functions of natural systems to manage aspects of the water cycle (Ahern 2007). GI often includes built infrastructure and natural systems, but sometimes may refer to strategic landscaping, open space conservation, or other efforts to intentionally maintain ecological functioning of natural and semi-natural systems (The Nature Conservancy 2013; Firehock & Walker 2015). By maintaining natural processes, GI often provides multi-benefit solutions for water management (Diringer *et al.* 2019). It replaces the functionality that has traditionally been provided by limited-purpose grey infrastructure, while providing additional benefits. Benefits range from the environmental and water management ones referred to above to social, economic, and health benefits (Lovell & Taylor 2013; European Commission 2012) that often set GI apart from its grey counterparts (Naumann *et al.* 2011). For example, a green roof can reduce storm water runoff and pollutant load while also decreasing the urban heat island effect, improving insulation of the building, and providing wildlife habitat.

GI can be employed at multiple scales, from the household level (Jia *et al.* 2016), to the urban and regional scale (Ahern 2007; Yang & Li 2013; Calderón-Contreras & Quiroz-Rosas 2017). A growing body of literature examines the management of GI, focusing predominantly on the use of small-scale GI installations (Young 2011; Abell *et al.* 2017; Liu & Jensen 2018), or medium scale GI in urban areas (Young 2011; Abell *et al.* 2017; Brears 2018). Less attention has focused on larger-scale GI projects and programs, for which literature has emerged on the contributions that larger GI have on the watershed scale effects on nutrient fluxes, water quality, and other catchment scale effects (Yang & Li 2013; Pennino *et al.* 2016; Golden & Hoghooghi 2018). with scarce reference to governance.

This paper focuses on LSGI, which we define as installations or systems of green infrastructure that have a material impact on water security at a watershed scale. LSGI includes systems of distributed stormwater installations like green roofs, vegetated swales, and permeable pavement (URI 2019), as well as large-scale projects that preserve, restore, or modify forests, riparian buffers, or wetlands (NYSDEC 2011). Thus, LSGI incorporates stormwater management (EPA N.Db) with landscape connectivity (Wright 2011), consistent with restoring the natural water cycle (AmericanRivers N.D.). By mimicking natural processes, GI and LSGI perform functions like flood risk reduction that have traditionally been handled by grey infrastructure, while delivering an array of additional benefits to ecosystems and communities (Talberth & Hanson 2012; Demuzere 2014; Green Nylen & Kiparsky 2015).

LSGI can reconcile multiple competing elements of water security in ways grey infrastructure cannot. For example, a 'horizonal levee' may improve water quality, sequester carbon, and reduce flood risk, while offering other co-benefits such as enhanced habitat for wildlife and sea level rise mitigation (The Nature Conservancy 2013). As an alternative to a hardened seawall, a horizontal levee can protect wastewater treatment infrastructure against storm surges, employing a sloped, vegetated surface to break waves (OLSD 2015). Unlike a seawall, the design improves water quality, provides habitat, and increases climate resiliency and aesthetic appeal (OLSD 2015). Table 1 summarizes the differences between grey infrastructure and LSGI.

LSGI governance to achieve water security

As previously mentioned, LSGI is increasingly well studied and widely accepted on its technical merit. But even as experience grows with LSGI, understanding how best to manage and govern this new class of infrastructure lags. As water infrastructure around the world reaches the end of its useful lifespan (ASCE 2011) and water security threats become more apparent, LSGI is emerging as an alternative to grey infrastructure (CLiGS 2013). Because of its integrative potential, it is unclear whether structures of governance will have to change to accommodate the implementation of LSGI. In this paper, we refer to governance as the full set of structures and processes through which public policy decisions are made and implemented (Ostrom 1990; Dietz *et al.* 2003; Lebel *et al.* 2006), with an emphasis on the regulatory processes, mechanisms, and organizations that set the stage for decision making (Lemos & Agrawal 2006).

The governance of water infrastructure has traditionally been led by disparate institutions, separately oriented around individual elements of water related services. Reflecting this institutional setting, physically interconnected elements of the water cycle are typically managed in a fragmented way by a collection of single- or

Table 1 | Characteristics of grey infrastructure and LSGI

	Grey infrastructure	LSGI
Financial costs	Capital costs plus operations and maintenance	Varies – may have lower capital costs, but higher operation and maintenance costs (Talberth & Hanson 2012; Talberth *et al.* 2012; EPA 2015)
Specificity of function	Can be optimized to perform specific functions well	By definition achieves multiple benefits, although potential to optimize natural processes for specific goals may vary
Performance	Generally effective at reaching primary goals, but often causes externalities (Iuell *et al.* 2003)	Relies upon integration of at least one natural process, potentially increasing variability and uncertainty in performance; integration potentially reduces externalities; performance risks could vary widely depending on operations and maintenance
Design life	Durable infrastructure can have design life of decades, but materials eventually fail and fall short of design functions	Different project lifespans possible, depending upon the operation and maintenance of the asset, but projects that make use of natural structures and processes can be designed to last significantly longer than grey infrastructure with appropriate maintenance, even indefinitely
Asset characteristics	Asset always depreciates over time	Asset may appreciate over time if maturity of biota results in better performance.

limited-purpose entities. Distinct water supply, wastewater treatment, flood risk management, and ecosystem management agencies each operate independently with their own goals and mandates.

Such fragmented governance approaches, however, do not align with the need for truly integrated water management (van Beek & Lincklaen Arriens 2014; Gerlak & Mukhtarov 2015). Transcending the current state of water security will require what Elzen and Wiezczorek refer to as a 'multi-actor, multi-factor, and multi-level transition' (Elzen & Wieczorek 2005), where new forms of environmental governance form 'innovative hybrids between the conventionally recognized social roles that markets, states, and, more recently, communities play' (Lemos & Agrawal 2006).

We hypothesize that the need to undertake this transition in water governance will involve changes across governance scales, processes and actors involved in environmental governance (Stoker 1998; Colebatch 2014) and that the multiplicity of benefits from LSGI will require from robust governance structures capable of juggling diverse needs, interests, and tradeoffs (Cook & Bakker 2012).

Environmental governance is transitioning from a siloed, static, top-down model towards approaches including polycentricity (Lemos & Agrawal 2006; Ostrom 2010), adaptive governance (Brears 2018), social learning and multi-level governance (Bakker & Morinville 2013). It remains unclear exactly how transitions to these new modes, including the development of appropriate strategies and policies, should or will occur (Elzen & Wieczorek 2005). Better understanding of governance dynamics in novel 'nature-based' approaches to water security, can help identify what has worked in the past and what is important for future implementation (Zingraff-Hamed *et al.* 2020).

This paper employs Lemos and Agrawal's (Lemos & Agrawal 2006; Bennett *et al.* 2019) polycentric governance framework. Lemos & Agrawal (2006) describe a triangular dynamic where state, market, and community interactions comprise governance based on the understanding of environmental governance as a 'set of regulatory processes, mechanisms[,] and organizations through which political actors influence environmental actions and outcomes' (Lemos & Agrawal 2006), and Bennet (Bennett *et al.* 2019) further describes the interactions as public private partnerships, community-industry partnerships, and collaborative management. Our hypothesis and research question hence focuses on answering whether and how new governance dynamics, opportunities and challenges may emerge around LSGI. The main objective of this inquiry is to draw lessons learned from existing cases that can guide the governance of this infrastructure as a tool to promote water security.

METHODS

LSGI has emerged as a class of multi-faceted tools with potential to improve water security, but uncertainty remains as to how LSGI should be governed, particularly given its multi-purpose and multi-objective nature.

Accordingly, high level motivating research questions include: What are challenges and opportunities for the governance of LSGI? Can existing water governance models be adapted to enable planning and implementation of projects with this emerging approach to multi-benefit water management? What needs and promising new approaches exist for funding and financing projects with multiple benefits and stakeholders? What incentives and approaches could further the adoption and diffusion of LSGI for water resilience?

To answer these questions the paper presents four original case studies of successful planning and implementation of LSGI. Because of the nature of the topic and the relative novelty and scarcity of these examples, we employed case study methods to explore and discover emergent qualitative phenomena (Yin 2009, p. 44). To systematize the findings across the four case studies, we employ congruence analysis to understand alignments with existing environmental governance theoretical frameworks (Annamalai *et al.* 2010), and to identify misalignments that could point to novel governance challenges and opportunities strictly related to LSGI. Furthermore, we employ thematic analysis (Lapadat 2010) across the four case studies to reveal prevailing challenges and opportunities for the governance of LSGI.

For case study selection, we developed a set of criteria, by which prospective cases were screened to:

1. Involve GI for water security, meeting our definition of LSGI as detailed above.
2. Be multi-benefit, addressing water security in a variety of ways, explicitly providing multiple benefits or a single main benefit coupled with side benefits;
3. Be large scale, consistent with our watershed-scale relevance criterion, described above. Small projects, or individual distributed projects were not considered, although programs that consist of large numbers of coordinated, distributed installations geared towards unified larger scale impacts were considered;
4. Be sufficiently mature, such that the infrastructure was at least partially developed and had demonstrated some success in accomplishing its objectives;
5. Have sufficient accessible information, including published and non-published data; and,
6. Be in the United States, to provide a degree of institutional and cultural commonality.

We identified eighteen potential case studies in the following locations: New York, Washington DC, Philadelphia, Rotterdam, Atlanta, Copenhagen, Singapore, London, Hamburg, Tianjin, Toronto, Phoenix, Vancuver, Manchester, Chicago, Melbourne, Sacramento, Denver, and Berlin. Using the criteria above, with reputational case sampling selection (Preissle & Le Compte 1984) using interviews with GI experts, academics and practitioners, we selected the final four case studies: Washington DC, Sacramento, Phoenix and Denver.

We gathered data through document review and interviews with key informants. Document review included a literature review of scholarly and technical publications (e.g., journal articles, reports, websites and other relevant sources) as well as review of current legal and public policy frameworks regulating green infrastructure. Sources included legislation, scientific articles, official websites, policy plans, maps, and other documentation totalling over 90 sources. Interviewees included relevant practitioners and experts in LSGI. We conducted 17 semi-structured interviews (Bernard 2000). A purposive criterion sampling strategy (Ritchie *et al.* 2014) was employed to recruit interviewees, which was supplemented by a snowball sampling methodology (Miles *et al.* 1994) to ensure expertise on the selected topics. Respondents included relevant decision makers and stakeholders from organizations including DC Water, Denver Water, USDA Forest Service, TNC, California Department of Fish and Wildlife, LimnoTech, Ducks Unlimited, EPA, and City of Phoenix Water Services, the Yolo Basin Foundation, Yolo Basin Wildlife Area, DC Department of Energy and Environment, City and County of Denver government officials, and UC Davis Center for Watershed Sciences. Interviews were conducted by phone, each lasting 60–90 minutes, supplemented by email exchanges.

For three of the cases (Yolo Bypass Wildlife Area, From Forests to Faucets Partnership, and DC Clean Rivers Project), the semi-structured interviews were organized to address three core topics via open ended questions. The topics were based on Lemos & Agrawals (2006) concept of environmental governance dynamics and addressed the governances of LSGI as a departure from siloed approaches to champion water security. The three core topics addressed were: First, state-community relationship questions focused on pre-existing or newly created policy frameworks for the installation and maintenance of GI, including co-management between state and community, and the level of stakeholder involvement from citizens and civil society organizations, as well as the private sector. Second, state-market relationship questions discussed whether and how public-private partnerships were invoked, what role the private sector played in the financing and success of these projects, and how private sector participation affected governance. Third, community-market relationship questions asked whether private-social partnerships existed and how they contributed to the inception and success of GI.

Semi-structured interviews for the Tres Rios Project case were conducted in the context of a parallel study of the relationship between regulation and innovation in the U.S. municipal wastewater sector. These interviews addressed an overlapping set of questions that contributed relevant data. The questions focused on how the project unfolded, what factors enabled or impeded it, what regulatory agencies and sectors of regulation were involved and how, and what lessons were learned that would be especially helpful to others, including utilities considering implementing similar projects and regulators considering whether and how to permit them. The data gathered for the Tres Rios case study touched on the same themes, but was overall of greater depth and breadth than the other three case studies, and we thus focused the thematic analysis on the subset of data paralleling the other three case studies.

The resulting array of textual materials and interview data were jointly analyzed using congruence analysis (Mills *et al.* 2010; Blatter & Haverland 2012). This approach allowed for empirical data from case studies to be compared with concepts drawn from relevant scholarship (Blatter & Haverland 2012). The analysis focused on understanding alignments and identifying possible misalignments with existing environmental governance theoretical frameworks, including adaptive governance, social learning and multi-level governance, with a special emphasis on Lemos and Agrawal model of polycentric governance. Furthermore, we employed partial thematic analysis (Guest *et al.* 2011) without systematic coding to identify themes across case studies following an abductive approach. Ultimately, the goal was to identify whether commonalities across case studies could inform the future planning and implementation of LSGI, or if the examples of LSGI in each case study were so unique that no cross-sectional themes emerge. Initial themes were identified for each case study and data type, then cross reviewed against the full data set to identify connections between themes, and surface potential overlaps. This method was used in an iterative process to combine data among case studies. The final themes described in the results sections are higher order analytical categories that were developed as a result of reorganization and merging of the identified themes: cost sharing, performance monitoring and legitimization.

The study was conducted in compliance with the UC Berkeley Institutional Review Board.

RESULTS AND DISCUSSION

Case study overviews

This section briefly introduces results from our research (Table 2), providing synopses of each case study including the motivating challenges, the water security benefits realized by LSGI, and the primary actors and institutional drivers. More details of each case study are then woven into the subsequent discussion.

Yolo Bypass Wildlife Area (Sacramento area, CA)

The floodplains of the Sacramento River historically supported a diverse riparian and freshwater marsh ecosystem. Urban development of Sacramento led to increased flood risk, and in 1911 Congress approved the Sacramento River Flood Control Project to repurpose the natural wetland basins of the Sacramento Valley as a flood control system. In the 1930s the 59,000 acre (24,000 ha) Yolo Bypass was set aside to prevent flooding in surrounding areas. 75% of the Yolo Bypass is privately owned agricultural land or wetlands managed for duck hunting clubs, while the rest is part of the Yolo Bypass Wildlife Area (YBWA). The YBWA was designated in 1992 when the first 3,700 acres was purchased by The Wildlife Conservation Board of the California Department of Fish and Game in an effort to restore the wildlife conservation and water management benefits from the wetland habitat while maintaining its flood control function. YBWA is a 16,800-acre parcel within the Yolo Bypass, owned and managed by the California Department of Fish and Wildlife (formerly Department of Fish and Game) for the benefit of birds traveling the Pacific Flyway. The area is managed to maintain the flood protection function of the Yolo Bypass while providing about 7,000 acres of restored wetlands and close to 7,000 acres leased by tenants of CDFW for commercial rice harvest and cattle grazing. The rice and grazing land is managed in a wildlife friendly manner while also providing income to the CDFW for management of the YBWA. The YBWA contributes to flood risk reduction for agricultural land and nearby towns, helps reestablish wetland habitat for water birds and other wildlife, and provides opportunities for cultural and educational programs for the community (CDFG&YBF 2008).

Table 2 | Summary of LSGI case studies examined in this study

	Yolo Bypass Wildlife Area	Forests to Faucets Partnership	DC Clean Rivers Project	Tres Rios Project
Location	Sacramento, California	Denver, Colorado	Washington, D.C	Maricopa County, Arizona
Timeframe for development of multi-benefit GI	1992-present	2010-present	2005-present	1995 to 2012
Key entities involved	California Department of Fish and Wildlife (CDFW), Yolo Basin Foundation, agricultural tenants	Denver Water, United States Forest Service, Colorado State Forest Service, Natural Resources Conservation Service	District of Columbia Water and Sewer Authority (DC Water) DC Department of Energy and the Environment (DOEE)	City of Phoenix, U.S. Army Corps of Engineers, Arizona Game and Fish Department, U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Flood Control District of Maricopa County, Brogdon Neighborhood Group, Arizona Department of Environmental Quality
Cost	$16 million	$33 million (1st phase), $33 million (2nd phase)	$2.7 billion	~$99 million for full-scale project (including flood control levee)
GI Approach	Managed reconnection of floodplain at a large scale	Forest restoration	Green Infrastructure for hydromodification	Constructed treatment wetland; riparian and wetland habitat restoration
Primary Benefits	Flood control	Fire Hazards Reduction, improve ecosystem functions	Protect and improve the health of District waterbodies by reducing storm water runoff that results or contributes to CSOs	Water quality Control, ecosystem restoration, flood control
Secondary Benefits	Working agricultural land, riparian and managed wetland, upland and grassland habitats, duck hunting, wildlife viewing, and educational opportunities. The Yolo Bypass Wildlife Area, area focused on habitat restoration	Water quality benefits with the reduction of the risk of post-fire sedimentation of reservoirs and the economic benefits from logging and local job growth	Aesthetic improvements, habitat, reduction in urban heat island effects, and new jobs for green infrastructure installation and maintenance	Recreation, environmental education, incidental groundwater recharge

From Forests to Faucets Partnership (Denver, CO)

The From Forest to Faucets Partnership (F2F) began in response to the costly consequences of a series of wildfires for the Denver Water collection system. Wildfires impact the quality of drinking water sources and the conditions for surrounding riparian ecosystems by changing the amount and timing of runoff, and through build-up of ash, soil erosion, and transport of fire retardants. Restoring and repairing Denver's water collection system after the Buffalo Creek and the Hayman wildfires in 1996 and 2002 cost more than $27 million to dredge reservoirs and remove sediment and debris. In order to avoid such catastrophes in the future, Denver Water and the United States Forest Service (USFS) started a collaboration focused on wildfire risk reduction through restoring 40,000 acres (16,000 hectares) of sensitive forests around the reservoir watersheds (Denver Water, 2017).

Colorado State Forest Service is an additional partner, conducting similar treatments on private and state-owned lands, and the Natural Resources Conservation Service is also a signing partner. Restoring forest and watershed ecosystems was a cost-effective means to reduce water quality risk from wildfires, resulting in improved water quality, reduced flooding, and freshwater ecosystem protection. Consistent with USFS's multiple use mission, additional benefits included protecting communities from wildfires.

DC Clean Rivers Project (Washington, D.C)

Hydromodification from land cover change in urban areas can increase peak stormwater flows that, when they exceed the capacity of combined stormwater and wastewater sewer systems, can result in urban flooding as well as combined sewer overflows (CSOs) that discharge untreated wastewater to receiving water bodies. In 2002, the District of Columbia Water and Sewer Authority (DC Water) developed a Long Term Control Plan (LTCP) to provide extra capacity and reduce CSOs via the construction of three tunnels (DCCRP 2012; 2015). The project evolved to eliminate the Rock Creek Tunnel and shorten the Potomac Tunnel to manage the runoff from Combined Sewer Outfall using green infrastructure projects, the DC Clean Rivers Project (DCCR). The program was the result of a lawsuit brought by a coalition of environmental groups against DC Water and the District of Columbia. After a Federal court found violations of the Federal Clean Water Act, a consent decree was signed in 2005 by (EPA N.Da) DC Water, the District of Columbia, the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Justice (DOJ). The decree and the associated LTCP establishes schedules for construction of CSO control facilities after previous systems were deemed unable to achieve water quality standards set by EPA. In 2015 after several years of study and significant investment, DC Water proposed a modification to the consent decree and LTCP to include GI to manage 133 acres in the Potomac sewershed and 365 acres in the Rock Creek sewershed for stormwater runoff. By managing stormwater runoff in GI facilities, models indicated that stormwater could be reduced or slowed sufficiently to shave peak flows and prevent CSOs. By October 2018, the installation of the first of five proposed GI projects in the Rock Creek Park sewershed began to provide environmental, economic, and health benefits that would have not been obtained with the tunnel. This project contributes to water security by improving the health of waterbodies for ecosystem health, and by reducing stormwater runoff (Van Wye 2012).

Tres Rios Project (Maricopa County, AZ)

The Tres Rios Project was initially envisioned in the 1990s with multiple water security related objectives: improving the quality of wastewater effluent discharged into the Salt River from the 91st Avenue Wastewater Treatment Plant, reducing flooding in neighboring communities, restoring riparian and wetland habitat, and enhancing the passive recreational and environmental education values of the area. It came about for a confluence of reasons. First, the City of Phoenix was facing the prospect of more stringent nutrient limitations for the wastewater treatment plant's discharges and considering how to respond (Gritzuk *et al.* 2001). Upgrading the plant, which the City of Phoenix operates on behalf of multiple cities in the Metropolitan Phoenix area, with conventional nutrient removal technology would have cost an estimated $635 million (Gritzuk *et al.* 2001). A much cheaper option would have been to reuse all the treated wastewater and avoid discharging effluent to the river altogether, but that would have starved the river of its primary source of flow during all but the wettest times of year (USACE 2000). Instead, the city – supported by an array of stakeholders, including the adjacent Gila River Indian Community, local residents, and a host of state and federal agencies – chose to develop treatment wetlands that would polish the effluent on its way to the river. This option would be more cost effective and energy efficient than traditional treatment plant upgrades (Suzzane Jumper & Rugg N.D.). At the same time, the U.S. Army Corps of Engineers wanted to address flooding along the Salt River (Infantino N.D.) that had caused extensive property damage in the past. Another objective was to restore wetland ecosystems lost to water depletion and upstream dams (Whittley N.D.).

Congress authorized partial funding for the estimated $99,320,000 Tres Rios project in 2000 (Water Resources Development Act of 2000, P.L. 106-541, Section 101(4)). The approximately 700 acre (283 ha) project (City of Phoenix N.D.a, N.D.b) was constructed largely between 2007 and 2012 (USACE 2011). It includes a flood control levee, effluent pump station, emergent wetlands, riparian corridors, and open water marsh areas to help restore native cottonwood and willow-based riparian corridors that were threatened by invasive plants (USACE 2011). In addition to their water treatment function, the wetlands now provide habitat for amphibians, insects, mammals, and waterfowl and provide space for community environmental education programs and leisure activities (City of Phoenix).

Analysis

Our case studies of LSGI and water security suggest that Lemos & Agrawal's (2006) model applies to these water governance processes, but also reveal further dynamics (Figure 1). These additional dynamics add richness to Lemos and Agrawal's model, including the potential for new approaches to cost sharing, the importance of monitoring, and the increased centrality of stakeholder cooperation for legitimization. The nuance added by analysis of these case studies adds complexity and governance dynamics not explicitly represented in the original model (shown in Figure 2).

The following sections describe three new process elements that we have incorporated into the model based on our analysis of key themes from the case studies. In particular, we find that cost sharing is often limited and informal in the case studies. We argue that cost sharing based formally on the range of benefits associated with LSGI represents one of the areas of greatest potential for expanding its implementation. The case studies suggest that broadening performance monitoring to encompass key secondary benefits will help to clarify how benefits and burdens are distributed across stakeholders, facilitate cost sharing, and enhance legitimacy. LSGI, like other emerging technologies, requires legitimization through multiple scales of stakeholder cooperation to build support and unlock potential funding mechanisms.

Cost sharing

The costs of LSGI projects can be of the same order as grey infrastructure projects, but since LSGI is not as well established (EPA 2017) funding such projects faces different challenges than comparable grey infrastructure. Because benefits accrue to multiple parties, in theory a diversity of funding streams could contribute to individual LSGI projects. At the same time, the primary proponents of a project that will provide multiple benefits may find it challenging to get other beneficiaries to contribute financially, especially those that have not been actively involved in project development. Greater clarity about how the project will distribute benefits among stakeholders could provide a basis for more productive conversations about who should bear the funding burden.

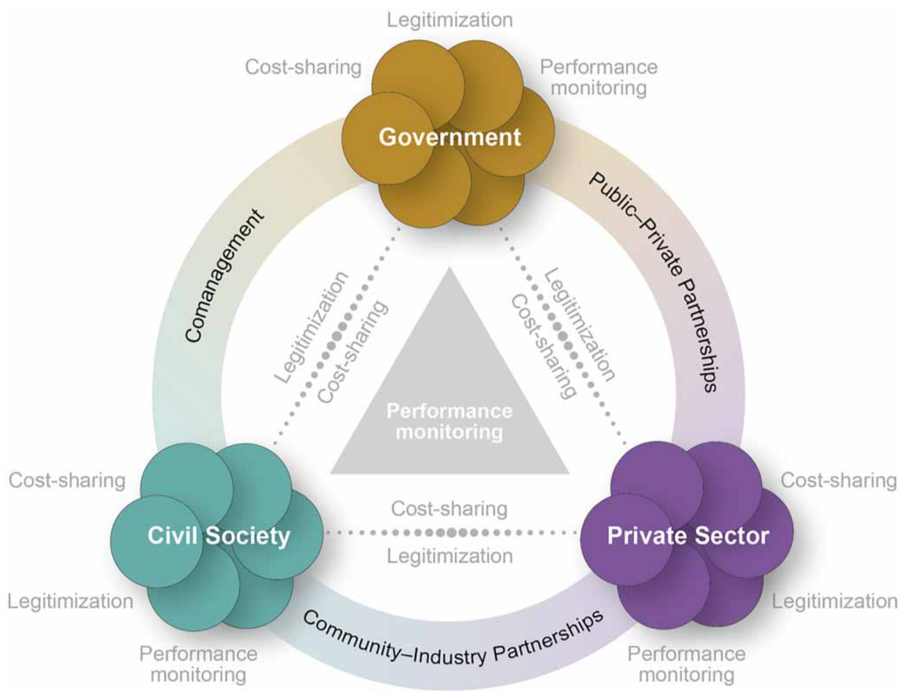

Figure 1 | Representation of mechanisms, strategies, and key dynamics of LSGI governance. This figure builds on Lemos and Agrawal's original conceptualization as modified by Bennett *et al.* (2019) (Figure 2), by adding process elements (cost sharing, performance monitoring, and legitimization) and indicating interactions among different entities within each category of actor (such as interactions between different government agencies).

Figure 2 | Inclusive governance of the blue economy. Adapted from Bennett *et al.* (2019), as an adaptation of Lemos & Agrawal (2006), page 310.

Benefit sharing is increasingly accepted as a principle that should guide resource management, and cost sharing (Diringer *et al.* 2020) is its corollary. Where stakeholder entitlements exist (Schroeder 2007), it follows that responsibility for sharing costs would follow as well. For example, governments sometimes partner with private sector entities on large infrastructure projects. Private operators can finance and construct a project, operate the project, generate income, and transfer ownership to the government at the end of a concession period (Abhay & Manju 2002). Such approaches tend to be based on monetized benefits and clearly defined revenue streams, such as tolls from road projects.

Analogues of these types of public-private partnership financing arrangements are not found in our case studies. Instead, the case studies suggest that while individual LSGI projects often aggregate multiple funding sources, rigorous alignment of costs and benefits is not yet the norm. Multiple sources of funding were accessed to cover LSGI costs in each case study except DCCR. Even though the full range of benefits and their distribution was not clearly defined, private sector and community entities often contributed financially, suggesting broad awareness of the value of LSGI. For instance, the YBWA depends on a combination of public funding sources and a private donor base, through the Yolo Basin Foundation. Program proponents have complemented this funding through state and federal grants for habitat restoration and enhancement within the YBWA. Similarly, for F2F, even though the two main sources of funding are Denver Water and USFS, corporations and NGOs have also contributed funding to expand work done by the government entities. Finally, in the case of Tres Rios, funding came from multiple public sources, including approximately 65% from the ACOE and 35% from the five cities in the Metropolitan Phoenix area that contribute wastewater to the 91st Avenue Wastewater Treatment Plant. Technical and financial assistance was also provided by the Flood Control District of Maricopa County (City of Phoenix N.Da), given the project's flood control component.

Such funding collaboration is promising, but many open questions remain about how benefits should be defined and distributed among stakeholders, and who should share the economic burden in exchange for receiving benefits. A basic challenge is defining what constitutes a benefit, who the beneficiaries are, how benefits are distributed, and how to quantify these relationships. This is particularly relevant in this comparision: the benefits associated with grey infrastructure are relatively well understood, but they are less straightforward for LSGI (Dixon 2012).

Part of the reason for perceived ambiguity in LSGI costs stems from the complexity of LSGI and its multiple benefits. But the perception of complexity arises because quantification of costs associated with grey infrastructure is generally oversimplified. Cost benefit assessments of traditional infrastructure have historically failed to consider externalities, such as environmental damage or disproportionate burdens on disadvantaged communities (Dixon 2012). Elements previously considered intangible or irrelevant can be crucial to assess the benefits derived from LSGI. For instance, community benefits of LSGI include the creation of environmental educational and cultural spaces and the provision of conservation value (Anand 2016). While there have been attempts to quantify such benefits, monetizing them is challenging (DCCRP 2015), and as with any developing technology, there is still inherent uncertainty around future project performance. Novel methods are emerging to enable the evaluation of the monetary and non-monetary benefits and burdens associated with LSGI (Gartner *et al.* 2013).

Internalizing a wider range of costs and benefits in apples-to-apples comparisons may further enhance LSGI accounting, since a range of projects impacts are often reduced relative to grey infrastructure, or even rank as net positive contributions to ecosystems and communities. The internalization of non-monetized ecosystem and community effects would represent a step forward for grey infrastructure, and a potentially essential element in valuing LSGI. In addition to ignoring near-term impacts as noted above (Dixon 2012), cost-benefit analysis methodologies discount long-term negative externalities that manifest only decades later, and omit cross-sectoral externalities and indirect costs (OECD 2019).

Also, as with any developing technology, there is inherent uncertainty around future project performance and hence around accounting for project costs and benefits. To partially address this challenge, novel methods are emerging to enable the evaluation of both monetary and non-monetary benefits and burdens associated with LSGI (Gartner *et al.* 2013). However, we did not find evidence in practice of the use of sophisticated benefit analyses and cost-sharing arrangements for LSGI to date. Instead, the case studies suggest that, perhaps due to the novelty of these approaches, the bulk of initial funding comes from general government funds, specific levies on taxpayers who directly benefit from the infrastructure, or fee structures designed to compensate for damages to the environment. For instance, the DCCR funding comes from taxes proportional to the total impervious area on a particular property and from in-lieu fees on larger developments intended to compensate for their environmental impacts and support mitigation measures.

Case studies employed a significant proportion of public funds, but most of the case studies also diversified their sources of funding in the absence of a single, stable revenue stream. These funding models worked to sustain and deliver on case studies' objectives, but also revealed challenges and constraints associated with the use of multiple sources of revenue, and with accounting for and attributing project benefits and costs. Bringing together disparate funders and funding sources can be non-trivial, even for a completely government-funded project. For example, a local government might access multiple funding sources targeted toward stormwater management, transportation, ecosystem restoration, and hazard mitigation to support a LSGI project (Georgetown Climate Center). Similarly, multiple entities whose different goals and priorities may be met by the multiple benefits of LSGI could each contribute to funding a project based on its anticipated value to their mission. However, those stakeholders or those sources of revenue come along with different agendas and objectives to be met. For example, many federal grants or loans are restricted to defined purposes that may not match the multi-benefit nature of GI, so they either cannot be used to fund, or can only be used to fund specific aspects of, GI projects (BASMAA 2018). Creative policy initiatives will be needed to develop stable funding schemes for future LSGI.

Furthermore, funders of all kinds may require a clear understanding of, and even a quantitative accounting of, the benefits that are meeting their goals to justify their funding support. If cost sharing is to be apportioned based on benefits to multiple collaborating entities, then benefits will need to be clearly defined and monitored, as discussed below, or stakeholders will need to agree to heuristic estimates. A key challenge is defining what constitutes a benefit, who the beneficiaries of each benefit are, how benefits are distributed, and how to quantify these relationships. Our case studies largely represent examples of ad hoc cost sharing. Whereas the risks, costs, and benefits associated with the construction of grey infrastructure are often perceived as relatively well understood by stakeholders, they are seen as less straightforward for LSGI.

Performance monitoring

Monitoring was consistently highlighted across case studies as a foundational element for LSGI governance. Measurable indicators are necessary for assessing the performance and effectiveness of any infrastructure (Pakzad & Osmond 2016), but may be particularly important in the context of LSGI as it strives to be accepted as an alternative solution to promote water security. Yet, our research suggests that monitoring and accounting for the range of benefits associated with LSGI – and how these accrue to various stakeholders – is challenging.

A range of challenges seemed to arise in establishing monitoring systems for LSGI. Effective governance of LSGI by multiple stakeholders requires a reconciliation of different views of what 'good performance' means. While monitoring efforts from existing GI and LSGI installations can serve as points of reference, they may not translate directly or easily to other projects and contexts. These difficulties are particularly salient when attempting to monitor how well a particular GI is increasing water security in its multiple dimensions (Economides 2014). Fortunately, emerging models for analyzing the costs and benefits of GI are starting to incorporate non-traditional environmental indicators such as recreation, social cohesion, and property value (Environmental Finance Center 2017). Further, emerging frameworks for impact assessment incorporate biophysical, psychological, and social benefits (Sullivan *et al.* 2003; EU Commission 2015), allowing for a more holistic performance evaluation.

Despite the desire to achieve multiple benefits with LSGI, monitoring in our case studies has been targeted more narrowly. In many cases, performance monitoring had one dominant focus, leaving secondary benefits unmonitored or less diligently tracked, at least initially. By definition, any single indicator will correlate incompletely with a suite of promised benefits, and thus be of limited use for quantitatively assessing multi-benefit projects. However, some interviewees suggested that focusing monitoring around a project's primary purpose(s) was helpful, because it enabled a more rapid establishment of a set of indicators, allowing the project to move forward despite limited budgets and staff capacity. For example, simplifying initial project objectives and indicators allowed the F2F partners to reach agreement on a basic initial monitoring regime and initiate restoration work more quickly and inexpensively.

While narrowing the focus of performance monitoring may reduce governance complexity and help LSGI projects work within capacity constraints, it also raises questions about what it means to truly manage a project for multiple benefits. At a minimum, performance monitoring should help project proponents and other stakeholders gauge whether a project is meeting critical measures of success and provide the information needed to test important assumptions and guide needed adjustments. In the case of the DCCR, monitoring indicators were designed to evaluate the effectiveness of the LSGI in meeting the requirements of its Amended Consent Decree. Since continuation of the DCCR currently hinges on achieving required runoff reductions and related reductions of overflow events to reach compliance with the terms of the Decree and LTCP, rather than on achieving specific water quality outcomes or other benefits, monitoring for the project focuses on the volume of stormwater runoff during and after precipitation events.

An added challenge for LSGI is that what monitoring is needed, desirable, and possible may change with time. Some monitoring requirements may decrease. For example, in the case of Tres Rios, EPA initially required extensive monitoring to enable assessment of and learning about the wetlands' impacts on water quality. When the accumulated data demonstrated the wetlands' effectiveness in achieving certain water quality requirements, EPA eliminated some requirements and modified others to achieve a more targeted monitoring program that reduced the burden on the City of Phoenix while continuing to ensure protection of water quality (EPA 2016). On the other hand, some monitoring requirements may increase over time. For example, monitoring related to secondary benefits might increase over time to enable a clearer understanding of the distribution of benefits and burdens among different stakeholders and, eventually, support the development of more robust and stable cost-sharing arrangements.

In sum, monitoring remains crucial for helping to determine the actual costs and benefits of an LSGI project. It facilitates accountability and enhances legitimacy for the particular project. Additionally, over the long term, the accumulation of information and experience is helping LSGI to become accepted as a viable and scalable solution.

Legitimization

Our case studies were consistent with the notion that novel water security solutions must undergo a process of legitimization to move from experimental novelty to accepted replacement for an incumbent technology, (Harris-Lovett *et al.* 2015) and with the notion that stakeholder cooperation is essential for environmental governance generally and for enhancing water security in particular (Akhmouch & Clavreul 2016). We refer to legitimacy as the generalized perception that a technology is desirable or appropriate within its social context (Johnson *et al.* 2006). It can also be described as the 'taken-for-grantedness' of a technology, organization, or process (Suchman 1995).

Such legitimization must occur at multiple scales if LSGI is to achieve broader adoption and diffusion. Local legitimization will be necessary around any given proposed LSGI project to bring sufficient support for its implementation over more traditional options. And more broadly, LSGI must become accepted as a legitimate alternative to grey infrastructure, through a process of challenging and rebuilding assumptions in the water and environmental management communities. Stakeholder engagement will be crucial to both processes.

Legitimacy was found to be important for the governance of LSGI at different stages of the project's lifecycle. LSGI often requires design creativity and bespoke technical development and is less familiar than traditional grey infrastructure. As unfamiliarity can exacerbate perceived uncertainty and result in a reluctance to commit to new projects, broader legitimacy could help normalize LSGI and increase support across the various stages of implementation. This is particularly relevant for LSGI as its performance can be variable across time due to its reliance on ecological systems and processes. Hence when comparing it to other alternatives, participants in a planning process may view grey infrastructure as proven for delivering a specific service. The case studies showed that the legitimacy of LSGI needed to be developed as a viable and advantageous alternative to traditional grey infrastructure.

The case studies were reflective of past findings that legitimacy can be enhanced via actions that address factors related to end users' interests (pragmatic legitimacy), broader societal values (moral legitimacy), and social and cultural assumptions (cognitive legitimacy) (Suchman 1995; Harris-Lovett *et al.* 2015). The case studies showed that stakeholder engagement and information provision are necessary to help legitimize and support a future LSGI project. DC Water held public meetings to educate the community on the nature and objectives of LGSI as a potential stormwater management solution in contrast to the more expensive single-benefit tunnel alternative. The meetings served to empower stakeholders to decide whether they support the initiative. The F2F program created a series of educational materials, videos, and data to help stakeholders understand the importance of healthy forested areas for drinking water. The establishment of LSGI was also boosted through information sharing and cooperation within the government. In F2F, USFS and Denver Water each brought extensive complementary technical expertise (Culver *et al.* 2001), enabling the partners to develop an effective plan of action and convey the importance of forest thinning for watershed health to the utility's board. The Tres Rios Project and DCCR involved learning through demonstration wetlands and smaller scale GI projects before installation of the full LSGI.

Stakeholders' knowledge of LSGI and cooperation with others also supported the legitimization of future projects. Key roles included the provision of technical support and engagement with governing bodies. For instance, in the case of the DCCR, an NGO with a watershed health mission assisted in the design of implementation tools, co-authoring a best management practice guidebook (Center for Watershed Protection 2013) that project developers used to evaluate options and which helped gain support from developers and NGOs. Similarly, in Denver, an NGO-led study helped decision makers define and prioritize restoration work (FRWPDRWG 2013). In the YWBA case, NGO partners helped secure grant funding for ecosystem restoration, and contributed to the viability of the project as intermediaries with legislators and other decision makers. The community also facilitated the creation of the YBWA by engaging local and federal government, promoting inter-stakeholder consensus, and contributing to the analysis and coordination of existing legal obligations and policy objectives (Salcido 2012). Finally, in parallel with developing plans for the full-scale Tres Rios Project, a range of stakeholders contributed to a national guidance document outlining key considerations for constructed treatment wetlands (EPA 2000).

Together with stakeholder's contributions to legitimization, the case studies showed that legitimization itself was also a result of the planning and implementation in the project cycle of LSGI. Public information sessions, educational materials, and other communication aids helped normalize its use as an alternative to promote water security once the project has already been established. In this sense, stakeholder cooperation and legitimization were deeply intertwined. Tres Rios gained initial support as a wetland-based project through contrast to the alternative plan of upgrading the existing wastewater treatment plant with new filtering technology. The alternative technology would have been more costly and energy intensive and lacked the added benefits of ecosystem protection and flood control (Suzzane Jumper & Rugg N.D.). However, the long-term preservation of the wetland required stakeholder involvement and cooperation. The Tres Rios Project involved representatives of institutions such as the Flood Control District of Maricopa County, the Gila River Indian Community, the City of Phoenix, the multi-city Sub-Regional Operating Group (SROG), the US Army Corps of Engineers (USACE), and environmental organizations, as well as local residents (especially the Brogdon Neighborhood Group) and construction and engineering consultants (Infantino N.D.). These stakeholders gained an understanding of potential project benefits and cooperated to legitimize this solution in their respective institutions of origin. New partnerships continue to emerge. For F2F, Colorado State University has collaborated in the quantification of wildfire reduction and associated outcomes, supporting legitimacy through scientific justification for the implementation of future phases of the project. A related multi-stakeholder deliberation process has also allowed for a forest restoration monitoring system to be established, providing further information on the outcomes of the LSGI.

In these case studies, ongoing legitimization through the promotion of trust was also supported by cooperation in the form of interagency comanagmenet and relationships between government and civil society. Interviewees indicated that inter-agency trust was key to success, and was often built on prior collaborations and relationships. For instance, in the case of F2F, Denver Water and USFS had engaged in previous joint projects which had built trust among agency leaders. For instance, Denver Water had a longstanding relationship with USFS through the Front Range Roundtable, a coalition of stakeholders committed to forest health and fire risk mitigation. In the YBWA different elements of the project are managed by different agencies, and the whole system is governed by a web of memoranda of understanding (MOUs), permits, habitat management plans, and partnership agreements that help define roles and ease cooperation. The case studies showed that familiarity among parties was crucial to launching partnerships to undertake uncertain LSGI projects where parties must be willing to transcend organizational boundaries and bureaucratic barriers (Resetar *et al.* 2020).

Finally, we found that project legitimacy can also be aided by piggybacking on existing environmental governance processes that have already been broadly legitimized. When LSGI projects are included as part of existing governance tools, they gain legitimacy by extension, since they are consistent with the assumptions already made in these processes. Such legitimization by extension (Harris-Lovett *et al.* 2015) occurred as the projects in each of the four case studies have been incorporated into climate change vulnerability, risk, adaptation, or mitigation assessment and planning. For instance, Sacramento's Risk and Climate Change Vulnerability Assessments recognized specifically that the construction of the Yolo Bypass and other bypasses have greatly reduced the risks of flooding on the Sacramento River in the last decades (AMEC 2011; Ascent Environmental 2017). Denver's climate adaption plan highlights F2F as a watershed protection strategy to support water supply and overall ecosystem health, describing it as a climate adaptation and mitigation tool (Denver Environmental Health 2014). A multi-jurisdictional hazard mitigation plan identified flooding as a potential security threat and referenced the flood control benefits of the Tres Rios project (JE Fuller 2009). Finally, Washington DC's vulnerability assessment highlights nature-based GI as a way to address climate change impacts and reduce stormwater runoff and flooding (DOEE 2016).

The legitimization of LSGI remains in process for each of these cases, but the case studies suggest the value of considering legitimacy, and strategies to promote it, when planning for LSGI.

CONCLUSIONS

Growing acknowledgment of the need for holistic water security solutions is paralleled by the emergence of LSGI and recognition of its advantages relative to traditional grey infrastructure. Case studies of early LSGI implementation highlight how the governance of LSGI lags behind its technical advances. The case studies also reveal that while LSGI projects have made promising strides in funding, performance monitoring, and legitimacy, significant room exists for further creative advancements in all these areas.

The multi-benefit nature of LSGI projects suggests the potential for individual projects to be supported by multiple funding sources. Indeed, while the case studies were primarily government-funded, each received funding from multiple entities, often from multiple sectors and with disparate interests in LSGI. This observation suggests that diverse stakeholders receive benefits in these LSGI projects and recognize them clearly enough to invest materially, an important substantive reflection of the multi-benefit outcomes of these projects.

Even where multiple parties contribute to funding LSGI projects, formal distributed funding arrangements were not maturely developed in any of the case studies. *Ad hoc* approaches to cost sharing enabled project development, but also generated uncertainty and inefficiency. In concept, LSGI may be well suited for novel approaches to financing. For example, financing vehicles could be envisioned that monetize multiple benefits could access sources of private capital in ways not served by traditional financing. Financing schemes could also be designed to formally align funding contributions from disparate entities with the benefits most directly related to their interests. But the case studies did not reveal such financing innovations. Better understanding of the goals for each stakeholder, matched with the relative benefits and costs of each project could pave the way for greater precision around who should bear which costs in jointly funded projects.

Performance monitoring is an essential element for LSGI projects and could enable greater precision in their financing. All the case studies involved efforts to monitor and quantify performance. This fact partly reflects the emerging nature of these techniques – grey infrastructure projects which use established and trusted approaches are not typically monitored for their primary performance goals, while LSGI still by and large needs to demonstrate basic efficacy.

Although all our cases were described by proponents and observers as multi-benefit, the performance of these LSGI projects was often measured based on a single predominant benefit, while the other benefits were not tracked, or were only partially tracked. In some cases, simplified monitoring appears to enable initial progress in project implementation and foster a collective focus on a common objective. Ultimately, more granular performance monitoring will be crucial to demonstrating whether and how LSGI projects are meeting the full range of project goals, validating how LSGI performs in comparison to grey infrastructure alternatives, and developing a robust basis for formal cost sharing. However, designing an appropriate monitoring system can be daunting and contentious. When attempting to develop monitoring systems that can deliver a clearer picture of the performance of LSGI, it may be necessary to reconcile different stakeholder's views of what 'good performance' means, as different outcomes will be seen as having more or less value depending on the actor's expectations for LSGI. Comprehensive monitoring of the range of LSGI benefits would be resource intensive and represents a key frontier for LSGI implementation.

A broad process of legitimization will be required to position LSGI as an advantageous alternative to the use of traditional grey infrastructure, and is also an important element in enabling solutions to the other financing and implementation issues discussed in this paper. Despite increasing technical sophistication, LSGI is still often perceived as an unfamiliar and unproven alternative for water management. However, information provision to stakeholders, the inclusion of LSGI within already legitimized frameworks, as well as the involvement of those stakeholders already familiar and supportive of LSGI have the potential to improve the legitimization of LSGI.

Stakeholder cooperation is a crucial ingredient for fostering legitimacy within these projects and a key element of good governance. Stakeholders helped enable viable projects through technical contributions and advocating for different sources of funding. Stakeholder collaboration helped traditionally disconnected government agencies to rally around the multiple-benefit nature of LSGI, facilitating project implementation. Cooperation helped develop trust among agencies, through defining common goals, establishing clear objectives and formal agreements, and establishing channels to share prior knowledge and relevant experience. LSGI proponents seeking successful implementation would be well served to invest in the hard work of fostering stakeholder cooperation.

Taking a broader view, policy initiatives may suggest reasons for optimism. In fact, federal legislation and guidance increasingly identify green infrastructure as a priority. For example, the 2019 Water Infrastructure Improvement Act directed the EPA to 'promote the use of green infrastructure in, and coordinate the integration of green infrastructure into, permitting and enforcement under [the Clean Water Act]…, planning efforts, research, technical assistance, and funding guidance' (33 U.S.C. § 1,377a; see also 33 U.S.C. § § 1,268(c)(ii), 1,301(f)(2), 1,342(s)(B)(ii)). Furthermore, California recently established a new Division of Multi-Benefit Initiatives within its Department of Water Resources (Maven's Notebook 2019). While this Division is new and yet untested, its existence alone highlights greater recognition of the need to support efforts like LSGI. While the case studies presented here suggest the potential for cautious generalization in the U.S., the insights from these case studies will need to be refined and validated as other case studies of LSGI emerge over time. Further, the inquiry described in this paper would need to be done in other governance contexts (e.g., outside the U.S.) to understand the potential broader applicability of these ideas.

While we leave comprehensive treatment of policy initiatives for further work, these examples provide hope that top-down efforts may complement local innovation in governance occurring at the level of individual LSGI projects, and in combination accelerate the development of multi-benefit projects for water security. The potential of LSGI is alluring, and these case studies support the deeper notion that the softer challenges of governance can be as difficult and important as technical feasibility in efforts to advance environmental solutions.

ACKNOWLEDGEMENTS

We thank Eric Hallstein, Sarah Heard, and Siobhan King for formative discussions and expert input at early stages of this project. The Nature Conservancy provided funding and substantive input on data gathering for a project on which we have drawn heavily to develop this article. The work was supported by funding from the Gordon and Betty Moore Foundation (Grant #9964) and UC Water through the University of California

Office of the President (UCOP Grant No. 13941). Funders had no involvement in the preparation of this paper. We are deeply grateful to the interviewees who generously shared their time and knowledge with us. Thoughtful reviews from Claire Harper, Thomas Timberlake, Claire Harper, Thomas Timber- lake, Robin Kulakow, Brian Van Wye, Matt Johnson, Matthew Espie, Dave Feliz, Roger Bales, Charles Bales, Heather Finden, Jacques Landy, Seth Charde, and Jordan Diamond, and anonymous reviewers helped improve a previous version of this paper.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 30 October 2020; accepted in revised form 9 September 2021. Available online 24 September 2021