TOPICAL REVIEW

Stormwater management and ecosystem services: a review

Liana Prudencio1,2 and Sarah E Null1
1 Department of Watershed Sciences, Utah State University, Logan, UT, United States of America
2 Author to whom any correspondence should be addressed.

E-mail: liana.prudencio@aggiemail.usu.edu

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Abstract
Researchers and water managers have turned to green stormwater infrastructure, such as bioswales, retention basins, wetlands, rain gardens, and urban green spaces to reduce flooding, augment surface water supplies, recharge groundwater, and improve water quality. It is increasingly clear that green stormwater infrastructure not only controls stormwater volume and timing, but also promotes ecosystem services, which are the benefits that ecosystems provide to humans. Yet there has been little synthesis focused on understanding how green stormwater management affects ecosystem services. The objectives of this paper are to review and synthesize published literature on ecosystem services and green stormwater infrastructure and identify gaps in research and understanding, establishing a foundation for research at the intersection of ecosystems services and green stormwater management. We reviewed 170 publications on stormwater management and ecosystem services, and summarized the state-of-the-science categorized by the four types of ecosystem services. Major findings show that: (1) most research was conducted at the parcel-scale and should expand to larger scales to more closely understand green stormwater infrastructure impacts, (2) nearly a third of papers developed frameworks for implementing green stormwater infrastructure and highlighted barriers, (3) papers discussed ecosystem services, but less than 40% quantified ecosystem services, (4) no geographic trends emerged, indicating interest in applying green stormwater infrastructure across different contexts, (5) studies increasingly integrate engineering, physical science, and social science approaches for holistic understanding, and (6) standardizing green stormwater infrastructure terminology would provide a more cohesive field of study than the diverse and often redundant terminology currently in use. We recommend that future research provide metrics and quantify ecosystem services, integrate disciplines to measure ecosystem services from green stormwater infrastructure, and better incorporate stormwater management into environmental policy. Our conclusions outline promising future research directions at the intersection of stormwater management and ecosystem services.

Introduction
Stormwater runoff provides ecosystem services, or benefits to people from the environment, including soil moisture, interflow, baseflow, groundwater recharge, and filtration of water through the environment (Roy et al 2008, Burns et al 2012, Barbosa et al 2012, Walsh et al 2016). Urbanization and increased population density alter land cover and land use, typically increasing impervious surfaces, such as asphalt, concrete, and buildings (Barbosa et al 2012). Conventional stormwater management directly routes runoff to nearby bodies of water through storm drains, gutters, and underground systems, and is also known as gray infrastructure. Gray stormwater infrastructure reduces ecosystems services from stormwater (Roy et al 2008) by reducing infiltration and groundwater recharge, and contaminating stormwater as runoff over impervious surfaces picks up pollutants such as heavy metals, suspended solids, nutrients, salts, oil and hydrocarbons (Tshihrintzis and Hamid 1997).
Additionally, climate change affects stormwater and urban runoff. For example, snowfall is anticipated to shift to rainfall in mountain regions, resulting in increased winter rainfall and runoff. Winter runoff is considered a hazard, whereas spring snowmelt runoff is considered a water resources benefit (Knowles et al. 2006). Climate change may reduce summer baseflow in rivers, despite wet winters (Null and Prudencio 2016). Also, inter-annual variability is expected to increase with climate change (Thornton et al. 2014), leading to a re-distribution of wet and dry years (Rheinheimer et al. 2016, Null and Viers 2013). Very wet water years are likely to increase urban runoff and present changing conditions, and opportunities, for green stormwater infrastructure.

Researchers and water managers have started to investigate the effectiveness of green stormwater infrastructure, such as bioswales, retention and detention basins, rain barrels, green spaces, wetlands, green roofs, permeable pavements, and deep infiltration wells to reduce flooding, augment surface water supplies, recharge groundwater, and improve water quality (Roy et al. 2008, Burns et al. 2012, Dhakal and Chevalier 2016). Green stormwater infrastructure research increasingly shows that the benefits of stormwater management transcend controlling runoff volume and timing, but also provide valued ecosystem services, such as improved water quality, groundwater replenishment, recreation opportunities, and creation of diverse habitats (Dhakal and Chevalier 2016, Vogel et al. 2015). Green stormwater infrastructure may counter impacts from urbanization while also increasing natural capacity to buffer for anticipated climate change (Barbosa et al. 2012, Pyke et al. 2011, Hamel et al. 2013, Stephens et al. 2012).

Alternative stormwater management practices have a number of terms, including best management practices, green infrastructure, low-impact development, managed aquifer recharge, and stormwater harvesting (Vogel et al. 2015, Hoss et al. 2016). In this paper, we use the terms ‘gray stormwater infrastructure’ for engineered systems that directly route stormwater to downstream water bodies in urban or developed areas and ‘green stormwater infrastructure’ for alternative stormwater management that generates both human and ecosystem services (Keeley et al. 2013). We focus on green infrastructure implemented specifically to manage stormwater.

Ecosystem services frameworks are increasingly used in research to categorize and measure benefits that ecosystems provide to humans (Coutts and Hahn 2015). Ecosystem services are generally categorized into four types: (1) provisioning, such as water supply and production of food and energy, (2) regulating, such as temperature regulation and water purification, (3) cultural, such as aesthetics and recreation, and (4) supporting, such as habitat for aquatic and riparian species (Koppperoinen et al. 2014, Cameron and Blanusa 2016, Walsh et al. 2016, Burns et al. 2012). Through classifying stormwater research into an ecosystem services framework, we can understand changes to ecosystem services from urbanization and quantify benefits of shifting from gray to green stormwater infrastructure with anticipated global environmental change. Figure 1 shows (a) ecosystem services related to stormwater in natural environments and (b) how ecosystem services change due to urbanization coupled with climate change. As shown in the figure, ecosystem services, such as water purification, water infiltration, and groundwater storage are impaired in the urban environment from impervious surfaces, exposure to urban pollutants, and gray stormwater infrastructure.

To date, there has been no systematic review of research at the intersection of green stormwater management and ecosystem services. The objectives of this paper are to (1) review and synthesize published literature at the intersection of these topics and (2) identify knowledge gaps that could better inform decisions and policies on green stormwater infrastructure for ecosystem services. The synthesis provided will direct future stormwater management research and aid researchers and policy-makers in managing stormwater sustainably.

Methods/design

We searched primary literature publications in Thomson ISI Web of Science (1975–2017), Water Resources Abstracts (1967–2017), Sustainability Science Abstracts (1995–2017), and Scopus (1823–2017) databases that included the terms ‘stormwater’ (or ‘storm water’) and ‘ecosystem services’, as well as at least one green stormwater infrastructure term anywhere in the text (table 1). Researchers and managers use multiple terms for green stormwater infrastructure. These include broad descriptions, such as green infrastructure and low impact development, and specific types of infrastructure such as retention basins, wetlands, and green spaces (Greenway 2015, Klimas et al. 2016, Kopecka et al. 2017, Pataki et al. 2011). Our search was inclusive of these terms as long as the publication focused on green stormwater management and ecosystem services-related topics. The search returned 216 results from all four databases through October 2017, with 170 papers ultimately retained that focus on green stormwater management and ecosystem services.

Following the search in the four databases, each article was reviewed and coded by the category of ecosystem services it addressed, as well as sub-categories of ecosystem services (table 2). An article could address multiple ecosystem services types. We evaluated how the articles quantified and discussed each of the four categories of ecosystem services to understand benefits of green infrastructure, highlight categories that are under-represented in the literature, and identify where further ecosystem services-stormwater management research is needed.
Results and synthesis

The number of stormwater management publications that discuss ecosystem services substantially increased since 2005, when the first paper on these topics was published (figure 2). The number of stormwater papers on provisioning and regulating ecosystem services has been increasing faster than publications on cultural and supporting ecosystem services (figure 3). Table 2 categorizes the number of articles that discuss the four types of ecosystem services, as well as the most prominent subcategories of ecosystem services. We synthesize each category in the following four sections.

Provisioning services—Provisioning ecosystem services were the most common type of ecosystem services discussed in stormwater management papers. Researchers often did not explicitly use the term ‘provisioning’; however, the ecosystem services they describe fall under this category. Studies on stormwater runoff and green stormwater infrastructure provisioning services focused on water supply and the production of vegetation and biomass for energy, food, and water (Ackerman 2012, Gittleman et al. 2017, Mayer et al. 2012, Taylor and Lovell 2014). Cities and urban areas generate water through stormwater detention (Lundy and Wade 2011). While stormwater in cities creates flooding and pollution, it is often now viewed as a potential resource for water supply enhancement (Ibid.).

More specifically, researchers and stakeholders are looking to green stormwater management for climate resilient stormwater storage and supply (Voskamp and de Ven 2015, Shuster et al. 2007). Climate change and urbanization have challenged water reliability, and planning for sustainable water supply is increasingly pertinent (Xue et al. 2015). While interest in and articles on provisioning ecosystem services have increased over the years, the studies that quantify provisioning...
Table 1. Search terms.

| 'stormwater' OR 'storm water' AND 'ecosystem services' AND Any of the following green stormwater management-related terms: |
|---------------------------------------------------------------|
| - green infrastructure |
| - managed aquifer recharge |
| - low impact development |
| - best management practices |
| - stormwater harvesting |
| - stormwater capture |
| - green roofs |
| - basins |
| - wells |
| - rain barrels |
| - wetlands |
| - ponds |
| - permeable pavement |
| - permeable surfaces |
| - pervious pavement |
| - pervious surfaces |
| - rain gardens |
| - tree boxes |
| - swales |
| - r-tanks |
| - underground vaults |
| - green space |
| - sustainability |
| - climate adaptation |
| - management |

Regulating services, instead of simply mentioning that they exist, are few in number. Most of the articles that examine provisioning services of green stormwater infrastructure do so with discussions of the potential of green infrastructure to enhance stormwater retention for infiltration and water supplies, as well as frameworks for implementation (Voskamp and de Ven 2015). Some develop approaches, or identify strategies and challenges by outlining case studies (Guertin et al. 2015). For example, Guertin et al. (2015) applied a tool to simulate green infrastructure to maximize water supply on the neighborhood-scale in a semi-arid region, identifying multiple scenarios for green infrastructure implementation.

Researchers highlighted the significant effects of vegetation and biotic production on streamflow and runoff generation (Berland et al. 2017, Starry et al. 2011, Verbeeck et al. 2014). Berland et al. (2017) outlined the role of urban trees in stormwater management, emphasizing that trees are significantly connected to urban hydrology and can increase infiltration of stormwater. Lastly, researchers studied the provisioning of food from green stormwater infrastructure (Russo et al. 2017). This research identified ecosystem services of sustainably managing stormwater, showing that water management, food security, and community development from edible urban greenery and gardens are inter-related.

Regulating services—This category closely followed provisioning services in frequency of articles (figure 3, figure 4). Regulating services of stormwater are sometimes quantified for flood control, water purification, climate regulation, and carbon sequestration from green infrastructure (Berland and Hopton 2014, Ishimatsu et al. 2017, McPherson et al. 2011, Gao et al. 2015). Researchers such as Gao et al. (2015) modeled water quality improvement and flood mitigation from green stormwater management at the city-scale and found positive results. However, the majority of studies assessed the performance of a single type of green infrastructure, such as green roofs, rain gardens, or stormwater ponds at the parcel-scale to capture and treat stormwater runoff. Smaller scale experiments provided support for nutrient attenuation, flood control, and microclimate mitigation ecosystem services of green stormwater management (Adyel et al. 2016, Wardynski et al. 2012). Multiple studies have investigated the capabilities of green infrastructure to capture and store carbon as well (Merriman et al. 2017, McPherson et al. 2011, Bouchard et al. 2013, Kremer et al. 2015, Chen et al. 2014). These studies quantified carbon sequestration through carbon accumulation rates, carbon storage potential of vegetation and soil, and similar metrics. Overall, they support carbon sequestration from green infrastructure, with nuances from differing vegetation types and soil conditions (Ibid.).

Interestingly, researchers noted tradeoffs between regulating ecosystem services and provisioning services, as well as tradeoffs between different regulating services (Kuoppamaki et al. 2016, Nocco et al. 2016). Kuoppamaki et al. (2016) highlighted that green roofs reduce runoff volume but also expose runoff to more nutrients. Nocco et al. (2016) found tradeoffs between daytime evaporative cooling and nutrient reduction from rain gardens. These scholars argue that regulating services related to green stormwater infrastructure are more nuanced than provisioning services, and require attention to site-specific characteristics, like plant communities, land uses, and soil quality (Booth et al. 2016).

Cultural services—Of the 170 articles reviewed, 46 publications discussed cultural services related to stormwater management (figure 3). Several researchers conducted surveys and interviews with stakeholders, residents, officials, and decision-makers, on the perceptions and values of ecosystem services from green stormwater infrastructure (Kati and Jari 2016, Welsh and Mooney 2014). Overall, the interviews provided insight into the potential strategies and obstacles of green stormwater infrastructure by user group. Kati and Jari (2016) found differences in values held by residents, managers, and politicians. For example, residents expressed attachment to a park as green infrastructure because it holds cultural value, while managers expressed negative values toward the park. They argued that research should further understand these differences and find mutual values for future collaborative planning (Ibid.). Welsh and Mooney (2014) surveyed a community and interviewed experts, concluding
Table 2. Number of articles by ecosystem service category and example references by subcategory.

| Category             | Number of publications | Subcategories                                      | Example references                                                                 |
|----------------------|------------------------|----------------------------------------------------|-------------------------------------------------------------------------------------|
| **Provisioning**     | 119                    | production of vegetation/biotic material for food  | (Ackerman 2012, Gittleman et al 2017, Mayer et al 2012, Lovell and Taylor 2013,    |
| **Services**         |                        | and energy water supply and storage                | Berland et al 2017, Russo et al 2017 (Lundy and Wade 2011, Voskamp and de Ven        |
|                      |                        |                                                    | 2015, Shuster et al 2007, Xue et al 2015, Guertin et al 2015)                       |
| Regulating          | 108                    | water purification                                | (Adyel et al 2016, Bhomia et al 2015, Dagenais et al 2017, Heintzman et al 2015)   |
| **Services**         |                        | climate regulation                                | (Klimas et al 2016, Lundholm 2015, Verbeeck et al 2014, Buckland-Nicks et al 2016,|
|                      |                        | flood control                                     | Guerard et al 2017)                                                                 |
|                      |                        | carbon sequestration                              | (Berland and Hopton 2014, Guertin et al 2015, Ishimatsu et al 2017, Doherty et al|
| Cultural Services    | 46                     | economic/cultural/social values                   | 2014)                                                                             |
|                      |                        | recreation                                         | (Kati and Jani 2016, Attwater and Derry 2017, Garcia-Cuerva et al 2016, Kellogg    |
|                      |                        | education                                          | and Matheny 2006)                                                                  |
| Supporting Services  | 48                     | biodiversity and habitat                           | (Hassall 2014, Horsley et al 2016, Larson 2010, McDuffie et al 2015)              |

Figure 2. Number of stormwater-ecosystem services publications over time.

that increasing green infrastructure implementation has potential to improve community cohesion and resiliency on top of environmental benefits of green stormwater infrastructure. The cooperation of residents toward a common goal of improving ecosystem services in their community led to this social cohesion (Welsh and Mooney 2014). Other researchers concluded that participants’ willingness to pay for green infrastructure is linked to perceived aesthetics, as well as improved hydrologic function and water quality (MacDonald et al 2015, Londono Cadavid and Ando 2013). Some scholars viewed perceived social values as an avenue to support and incorporate green space and infrastructure in urban areas (Attwater and Derry 2017, Ghermandi 2016). Property values increase from green stormwater infrastructure, particularly near green spaces installed to manage stormwater (Mazzotta et al 2014).

Educational and recreational values from green infrastructure were discussed in the literature, with most authors asserting that green infrastructure, such as urban ponds, offer education and recreation services, and consequently improve community welfare (Hassall 2014, Kandulu et al 2014). Individual perceptions of these services, as well as the potential of recreation and education, were sometimes measured (Wilson 2012, McDuffie et al 2015, Kremer et al 2015). An example study, conducted by Wilson (2012), found that individuals hold views that are more positive when green stormwater infrastructure includes recreation and educational opportunities.

Supporting services—The majority of the research on supporting services of green stormwater management was centered on biodiversity and habitat provided by green infrastructure (Hassall and Anderson 2015, Greenway 2015). With altered landscapes
leading to habitat and biodiversity loss, the main argument was that green infrastructure preserves viable species’ populations needed to support ecosystem processes, diversity, and consequently other ecosystem services (Taylor and Lovell 2014, Attwater and Derry 2017, Kopecka et al 2017). However, few researchers quantified the impacts of green stormwater management on supporting services for specific habitats and species. Greenway (2015) showed that constructed stormwater wetlands provide habitat for macroinvertebrates and measured biodiversity with species richness as a metric. While studies link green space biodiversity to human well-being, researchers recognized that biodiversity preservation is more nuanced than merely implementing green infrastructure (Kopecka et al 2017, Hassall and Anderson 2015). They recommended more thorough examination of potential ecosystem services and limitations of green stormwater infrastructure for conservation (Dagenais et al 2017, Mitsova et al 2011).

Discussion

Major findings

We identified six major findings that summarize the state of research at the intersection of green stormwater management and ecosystem services. These are discussed in turn below. First, most of the experiments and studies on green stormwater management...
were conducted at the parcel-scale (Zöllch et al 2017, Buckland-Nicks et al 2016, Wardynski et al 2012, Adyel et al 2016, Natarajan and Davis 2016). While implementation of green stormwater infrastructure at small scales suggests improvements to provisioning, regulating, cultural, and supporting ecosystem services, more research is warranted at the watershed-scale to quantify regional-scale effects. Watershed-scale modeling provides an appropriate method to upscale parcel- and neighborhood-scale results (Feng et al 2016, Garcia-Cuerva et al 2016, McDonough et al 2016, Wu et al 2013).

Second, 49 of the publications (29%) included frameworks or approaches for implementing green stormwater management and highlighted barriers to implementation. Frameworks were developed for different cities and regions, and focused on facilitating decision-making and spatial planning of green stormwater management (Carter and Fowler 2008, Chaffin et al 2016, Dhakal and Chevalier 2016, Hoang and Fenner 2016, Lundy and Wade 2011, Perales-Momparler et al 2015, Schuch et al 2017, Shuster and Garmestani 2015). Authors developed frameworks based on literature reviews and case studies, and they centered their approaches on using green stormwater infrastructure to mitigate for lost ecosystem services from urbanization, adapt to climate change, or integrate multiple ecosystem services into stormwater management (Ibid.). Several of the frameworks emphasized barriers to implementing green stormwater infrastructure. They attributed jurisdictional overlap and insufficient incentives for partnerships between the different groups and individuals as barriers to green stormwater management (Shuster and Garmestani 2015, Chaffin et al 2016, Dhakal and Chevalier 2016). Different groups also had fragmented responsibilities and interests that conflict, which in turn creates barriers for organized management (Perales-Momparler et al 2015, Hoang and Fenner 2016). Some authors point to inertia and lack of financial and political support as an additional barrier to green stormwater infrastructure (Carter and Fowler 2008, Shuster and Garmestani 2015).

Third, only 39% of publications quantified ecosystem services from green stormwater management (figure 4). Many papers summarized general relationships, or assumed relationships, between green stormwater infrastructure and ecosystem services. Regulating services were most often quantified, with diversity in the metrics used, such as carbon accumulation and phosphorus accretion (Merriman et al 2017, Bhomia et al 2015). The other three categories of ecosystem services were rarely quantified. Quantifying changes to ecosystem services from green stormwater infrastructure is a needed direction for the future to inform and improve green stormwater design, decision-making, planning, and implementation.

A fourth finding is that there were no significant geographic patterns of research on green stormwater management and ecosystem services. Research has been conducted in a variety of places and climates, including Australia, France, the United States, and China (Schuch et al 2017, Maillard and Imfeld 2014, Bhomia et al 2015, Moore and Hunt 2012, Yang et al 2015, Gao et al 2015). However, there is a lack of research at the intersection of ecosystem services and green stormwater management in developing regions and countries. This finding indicates that multiple researchers are interested in and are investigating the potential of green stormwater infrastructure to provide ecosystem services. While this is a promising finding, future research should investigate whether green stormwater infrastructure provides ecosystem services differently across cultural, socioeconomic, and sociopolitical settings.

Fifth, studies increasingly integrate engineering, physical sciences, and social sciences in their research questions. The ecosystem services approach to evaluating green stormwater management lends itself to interdisciplinary research. Nevertheless, research that incorporates all three of these disciplines are limited in number, with several of the publications coming from urban planning and landscape architecture venues (Dagenais et al 2017, Hoang and Fenner 2016, Horsley et al 2016, McPherson et al 2011, Yang et al 2013). Further examination of multiple ecosystem services in a single study would also progress the literature. The maintenance and delivery of one ecosystem service happens in relation to other ecosystem services, and therefore, these connections between ecosystem services should be studied. In a similar vein, different combinations of green stormwater infrastructure may be more suitable than relying on one type alone. Cities likely will benefit from implementing green infrastructure throughout their watershed, which should be explored in future research.

Sixth, overlapping and redundant green stormwater infrastructure terminology is an impediment to research discovery. We searched for 25 unique terms in addition to ‘stormwater’ and ‘ecosystem services’ (table 1). It was necessary to search for individual types of green stormwater infrastructure, like stormwater ponds, rain gardens, or green roofs for comprehensive review (Monaghan et al 2016, Moore and Hunt 2011, Olguín et al 2017, Rumble and Gange 2017, Starrs et al 2011, Squier et al 2014, Chaffin et al 2016, Gittleman et al 2017). Similarly, many terms overlap somewhat, such as green infrastructure, green space, and low impact development (Cizek 2014, Klimas et al 2016, Mayer et al 2012). While these terms are not completely redundant, they obscure search results. In addition, there is no consensus on the spelling of stormwater, with some researchers writing it as a single word, some as a hyphenated word, and some as two words. Most articles wrote stormwater as a single word and following this norm will facilitate future literature searches. We also recommend authors include a catchall term such as ‘green stormwater
Future research directions for managing ecosystems services with green stormwater infrastructure

Through organizing existing green stormwater infrastructure literature into the four categories of ecosystem services, we identified research gaps in all categories. First, many researchers referred qualitatively to the ecosystem services offered by green stormwater infrastructure, and few researchers quantified the value or impact of those benefits. Also, existing studies typically focus on one type of ecosystem service; however, utilizing an ecosystem services framework encourages multi-disciplinary research for green stormwater management (Lundy and Wade 2011). Finally, lack of policy and institutional support for green stormwater infrastructure to provide ecosystem services was a barrier mentioned in papers in all categories of ecosystem services. With the remainder of the discussion, we outline three main directions for future research at the intersection of stormwater management and ecosystem services: (1) quantifying ecosystem services, (2) integrating engineering, environmental, and social criteria into stormwater management, and (3) integrating stormwater management and water policy.

Quantifying ecosystem services is rarely done but is needed to better understand the extent to which green stormwater infrastructure may enhance or degrade ecosystem services. Ecosystem services are sometimes monetized (Costanza et al 1997), but need not be economically valued to be measured. Identifying metrics to measure ecosystem services will allow researchers and stormwater managers to reduce undesirable impacts of stormwater, like erosion and water quality degradation, while enhancing ecosystem services from green stormwater infrastructure. Measuring specific ecosystem services from green stormwater infrastructure will inform decisions about stormwater management in varying climates, regions, and for different design objectives. Figure 5 illustrates the contribution of quantifying ecosystem services from green infrastructure to management decisions. By evaluating the quantity, location, and timing of ecosystem services from green infrastructure alternatives, decision-makers are better primed for implementing stormwater management plans to meet desired stormwater ecosystem services.

We provide example metrics to measure all categories of ecosystem services in table 3. Green stormwater infrastructure research could be expanded to measure surface and groundwater supply, and the effects of urbanization and climate change on these services (Dillon et al 2009a, Dillon et al 2009b, Maliva 2014). Quantifying possible tradeoffs between increasing aquifer storage and introducing water quality contaminants to groundwater is a needed direction to quantify competing ecosystem services. Similarly, measuring the effects of green stormwater infrastructure design for water purification and stream temperature management is warranted, especially at the Watershed- or regional-scale for spatial planning purposes. While considerable research has evaluated perceptions and values of ecosystem services from green stormwater infrastructure, cultural components of ecosystem services should be measured in future research. This could include change in property values from proximity to green stormwater projects (Mazzotta et al 2014) or recreational metrics, such as number of boatable days in rivers (Ligare et al 2012). Research on supporting services of stormwater management is least often studied. Green stormwater infrastructure could focus on biodiversity as an umbrella goal for resiliency of several ecosystem services in the urban setting (Connon et al 2016).

Secondly, integrating engineering, social, and environmental criteria is needed to identify the most appropriate and effective stormwater infrastructure, and to evaluate synergies between disciplines for holistic stormwater decision-making and management (Hale et al 2015). Engineering criteria are the basis for infrastructure and technological solutions. Environmental criteria maintain ecosystem functions of interest. Social criteria highlight economic, political, and cultural values, perceptions, and barriers to implementation. Figure 6 shows examples of these intersections. Our review showed that provisioning and regulating ecosystem services received more attention than other ecosystem services, but were typically evaluated one at a time (Gittleman et al 2017, Mogollon et al 2016, Griffin et al 2014). These studies offer initial findings that support green stormwater management to maintain ecosystem services, but future research could provide a deeper investigation of green infrastructure through evaluating research questions about multiple types of ecosystem services.

Finally, we encourage scholars to quantify the social, economic, and policy benefits of green stormwater infrastructure so that green stormwater management can be integrated into environment-related policy. Stormwater governance in the US is decentralized, which creates barriers from jurisdictional overlap or lack of mandate and authority in managing stormwater (Freeman 2000, Armstrong 2015, Shuster and Garmestani 2015, Chaffin et al 2016, Dhakal and Chevalier 2016). By further integrating and explicitly addressing stormwater management research, stakeholders and decision-makers can be better informed to implement effective and resilient management practices. Here we briefly mention four policy routes that have potential to support the investigation and implementation of sustainable stormwater practices in the US. Similar opportunities exist globally.

First, total maximum daily load (TMDL) plans, which are required for contaminated water bodies by the Clean Water Act (Elshorbagy et al 2005), are an example method of further incorporating green stormwater management into environmental-related
Figure 5. Connection between quantifying green stormwater infrastructure ecosystem services and management decisions.

Table 3. Ecosystem services—stormwater management research subareas and example metrics to quantify ecosystem services from green stormwater infrastructure.

| Category          | Futures research subareas                                      | Example metrics to quantify ecosystem services                                           |
|-------------------|----------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Provisioning      | Population growth and water supply reliability                | Water volume, cubic meters per month (m³/mo⁻¹)                                            |
|                   | Water storage and climate adaptation                            | Groundwater recharged, m · mo⁻³, or aquifer water level, m                                |
| Regulating        | Water quality improvement                                       | Temperature and contaminant change, ΔC, or dollars per pound of contaminant removed, $/lb C|
|                   | Flood mitigation                                               | Reduction in flood discharge magnitude, m s⁻³, or reduction in flood duration (hours)   |
| Cultural          | Pricing strategies for cultural services                       | Residents’ willingness to pay for aesthetics and recreational opportunities from green stormwater infrastructure, $ |
|                   | Revenue and property values                                    | Property value change from proximity to green stormwater infrastructure, $                |
| Supporting        | Biodiversity                                                  | Number of species, count                                                                  |
|                   | Perceptions of resource managers and residents                 | Statistical analyses on managers’ and residents’ perceptions of species and habitats, chi-square statistic |
policy. Plans set limits on acceptable pollutant loads and outline needed changes to reduce contaminant loads. As the ecosystem services of green stormwater infrastructure for managing nutrients are measured, and as tradeoffs between enhancing water supply and water quality impacts are quantified, green stormwater infrastructure could be a direct method to attain TMDL targets. Many TMDL plans have been designated for impaired water bodies across the US with recommendations for best management practices, including green stormwater infrastructure. However, little research has been conducted on the extent to which green stormwater infrastructure would need to be implemented to attain TMDL targets. Also, one component of the ESA is to address nonpoint source pollution, which is a significant part of stormwater runoff. Section 9 of the ESA requires protection of habitat for endangered fish and wildlife species. This, in turn, opens up legal possibilities to monitor and regulate nonpoint source pollution by increasing infiltration, water storage, and nutrient uptake through green stormwater infrastructure (Tzankova 2013). Local- and state-level groundwater policy regulates and allocates groundwater. These policies may support groundwater recharge and water quality control from stormwater management (Kubasek and Silverman 2005). Finally, researchers are increasingly studying the influence of green stormwater infrastructure on human health (Vogel et al 2015). Current research is connecting ecosystem services to human health and well-being in urban environments (Ibid.), leading to more research on the linkages between green infrastructure and ecosystem services. Public health concerns could encourage the implementation of green stormwater management (Coutts and Hahn 2015).

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**ORCID iDs**

Liana Prudencio https://orcid.org/0000-0001-5361-9841

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