Stormwater Management and Ecosystem Services: A Review

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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 disciplines and should fuseengineering, 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.

Keywords:
Green stormwater infrastructure, runoff, water supply, aquifer recharge, water quality, climate adaptation

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 (Tsihrintzis & 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 & 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 & 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 & 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 & 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 & 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 (Kopperoinen et al. 2014; Cameron & 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.

(a)

(b)

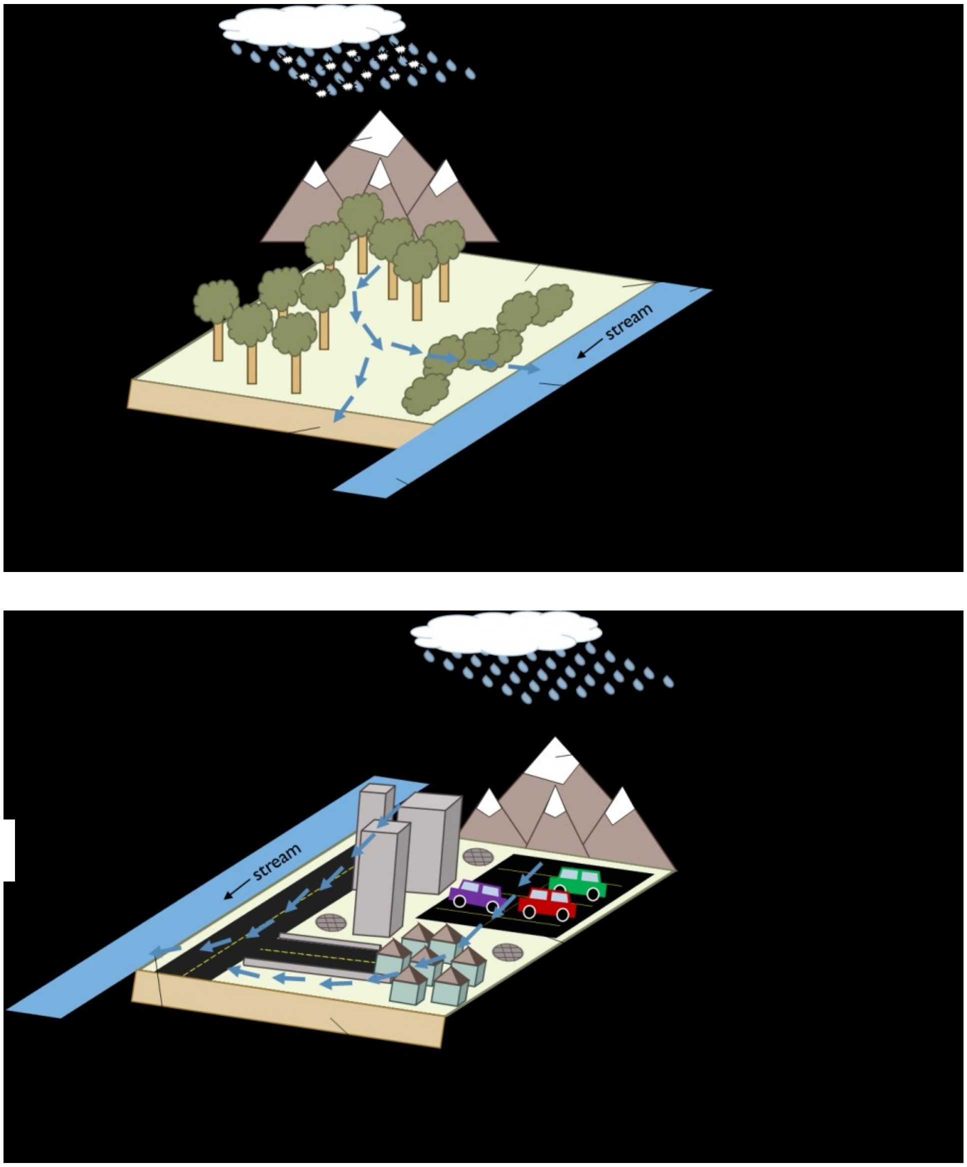

Figure 1 – (a) Ecosystem services related to stormwater in natural environments and (b) Environmental impacts from gray stormwater infrastructure, urbanization, and climate change

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 to 2017), Water Resources Abstracts (1967 to 2017), Sustainability Science Abstracts (1995 to 2017), and Scopus (1823 to 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. 2016a; 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.

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"

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 (F*igure 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.

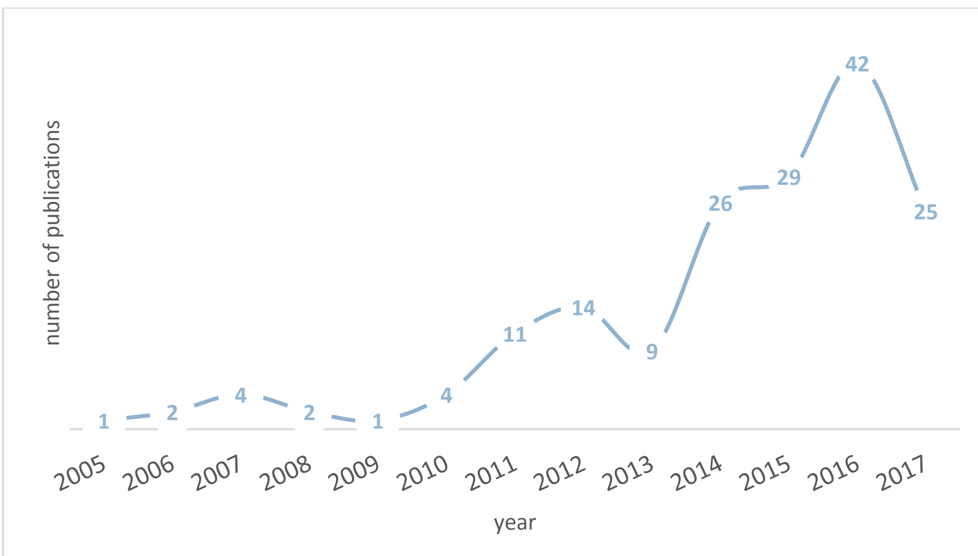

Figure 2 - Number of stormwater-ecosystem services publications over time

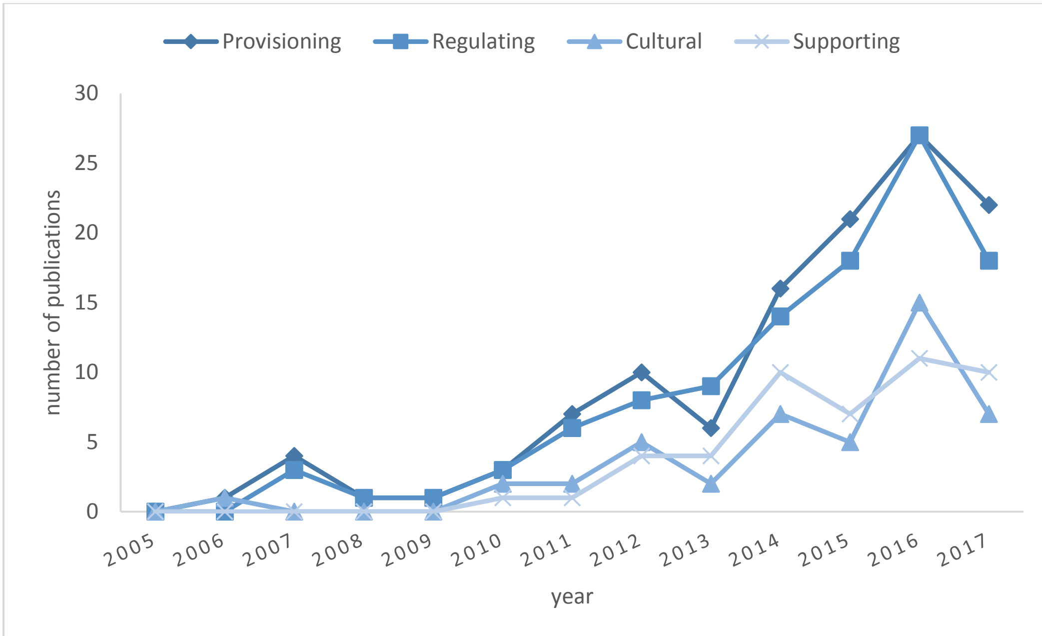

Figure 3 - Number of stormwater-ecosystem services publications over time by ecosystem service category

Table 2 - Number of articles by ecosystem service category and example references by subcategory

Category	***Number of Publications***	***Subcategories***	***Example References***
Provisioning Services	119	production of vegetation/biotic material for food and energy	(Ackerman 2012; Gittleman et al. 2017; Mayer et al. 2012; Lovell & Taylor 2013; Berland et al. 2017; Russo et al. 2017)
		water supply and storage	(Lundy & Wade 2011; Voskamp & de Ven 2015; Shuster et al. 2007; Xue et al. 2015; Guertin et al. 2015)
Regulating Services	108	water purification	(Adyel et al. 2016; Bhomia et al. 2015; Dagenais et al. 2017; Heintzman et al. 2015)
		climate regulation	(Klimas et al. 2016b; Lundholm 2015; Verbeeck et al. 2014; Buckland-Nicks et al. 2016; Gruwald et al. 2017)
		flood control	(Berland & Hopton 2014; Guertin et al. 2015; Ishimatsu et al. 2017; Doherty et al. 2014)
		carbon sequestration	(Merriman et al. 2017; McPherson et al. 2011; Bouchard et al. 2013; Kremer et al. 2015; Chen et al. 2014)
Cultural Services	46	economic/cultural/social values	(Kati & Jari 2016; Attwater & Derry 2017; Garcia-Cuerva et al. 2016; Kellogg & Matheny 2006)
		recreation	(Kandulu et al. 2014; Moore & Hunt 2012; Kremer et al. 2015; Ghermandi 2016)
		education	(Hassall 2014; Horsley et al. 2016; Larson 2010; McDuffie et al. 2015)
Supporting Services	48	biodiversity and habitat	(Hassall & Anderson 2015; Greenway 2015; Taylor & Lovell 2014; Attwater & Derry 2017; Kopecka et al. 2017)

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 & Lovell 2014). Cities and urban areas generate water through stormwater detention (Lundy & 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 & 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 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 & 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 & 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.

<u>Cultural Services</u> – 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 & Jari 2016; Welsh & Mooney 2014). Overall, the interviews provided insight into the potential strategies and obstacles of green stormwater infrastructure by user group. Kati & 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 & Mooney (2014) surveyed a community and interviewed experts, concluding 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 & 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 & Ando 2013). Some scholars viewed perceived social values as an avenue to support and incorporate green space and infrastructure in urban areas (Attwater & 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.

<u>Supporting Services</u> – The majority of the research on supporting services of green stormwater management was centered on biodiversity and habitat provided by green

infrastructure (Hassall & 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 & Lovell 2014; Attwater & 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 & 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 (Zölch et al. 2017; Buckland-Nicks et al. 2016; Wardynski et al. 2012; Adyel et al. 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 & Fowler 2008; Chaffin et al. 2016; Dhakal & Chevalier 2016; Hoang & Fenner 2016; Lundy & Wade 2011; Perales-Momparler et al. 2015; Schuch et al. 2017; Shuster & 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 & Garmestani 2015; Chaffin et al. 2016; Dhakal & 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 & Fenner 2016). Some authors point to inertia and lack of financial and political support as an additional barrier to green stormwater infrastructure (Carter & Fowler 2008; Shuster & 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.

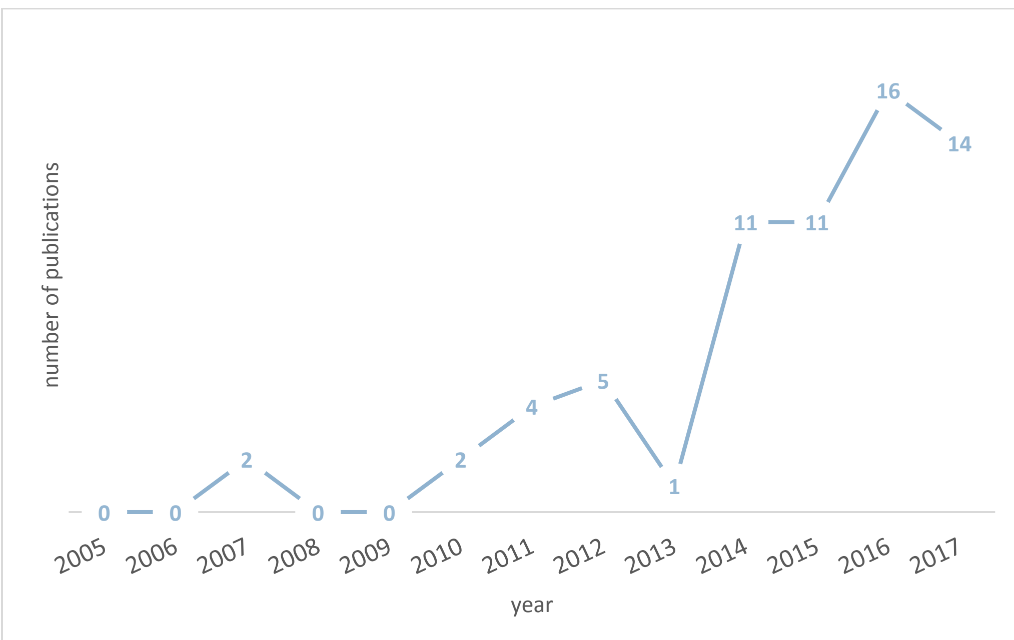

Figure 4 - Number of publications that quantify ecosystem services related to stormwater management

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 & Imfeld 2014; Bhomia et al. 2015; Moore & 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 & 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 & Hunt 2011; Olguin et al. 2017; Rumble & Gange 2017; Starry 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. 2016b; 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 infrastructure’ as a search keyword for a cohesive body of literature.

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 & 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.

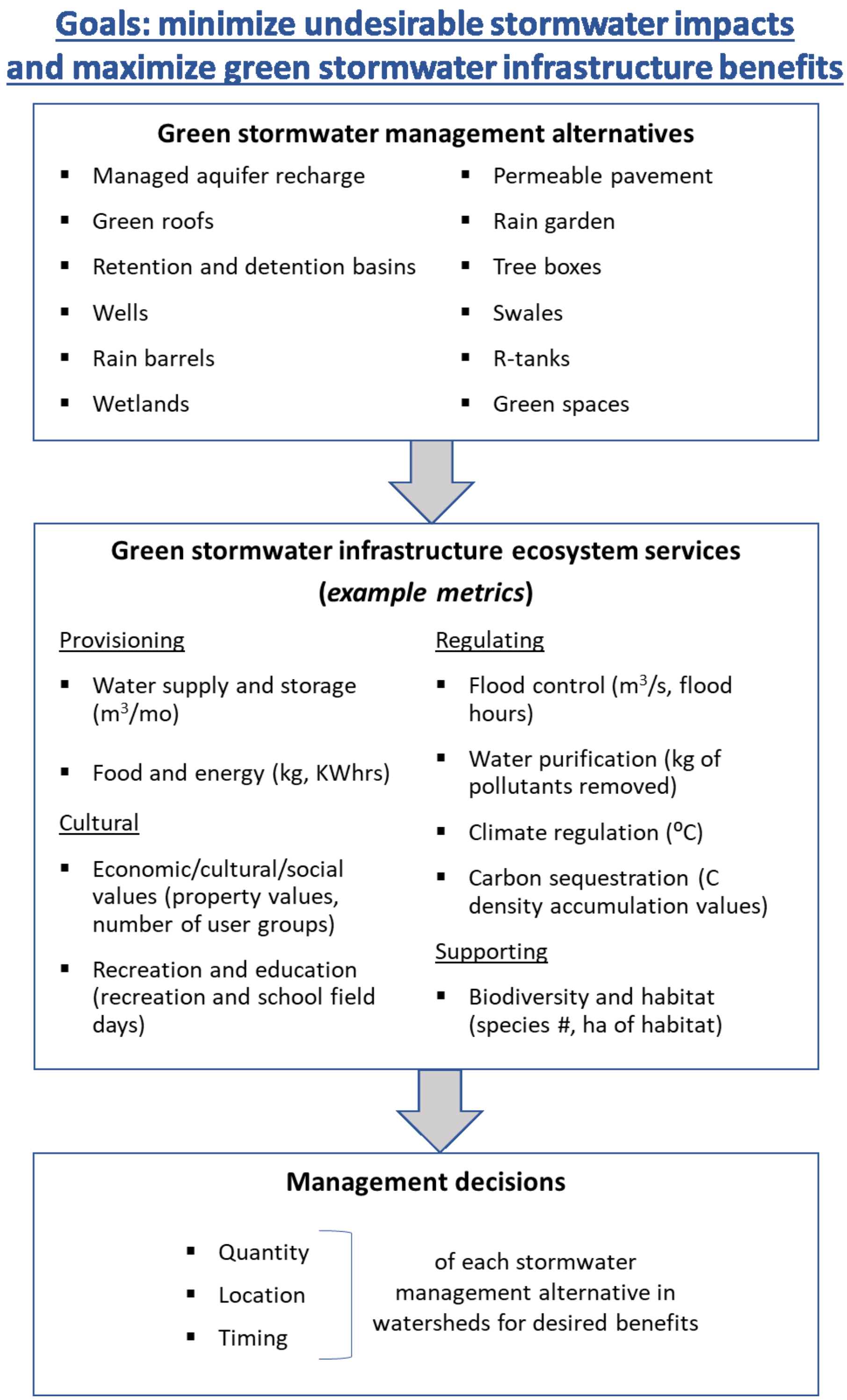

Figure 5 – Connection between quantifying green stormwater infrastructure ecosystem services and management decisions

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 (Connop et al. 2016).

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

Category	***Future Research Subareas***	***Example Metrics to Quantify Ecosystem Services***
Provisioning Services	Population growth and water supply reliability	Water volume, cubic meters per month (m^3/mo)
	Water storage and climate adaptation	Groundwater recharged, m^3/mo, or aquifer water level, m
Regulating Services	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^3/s, or reduction in flood duration (hours)
Cultural Services	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 Services	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

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.

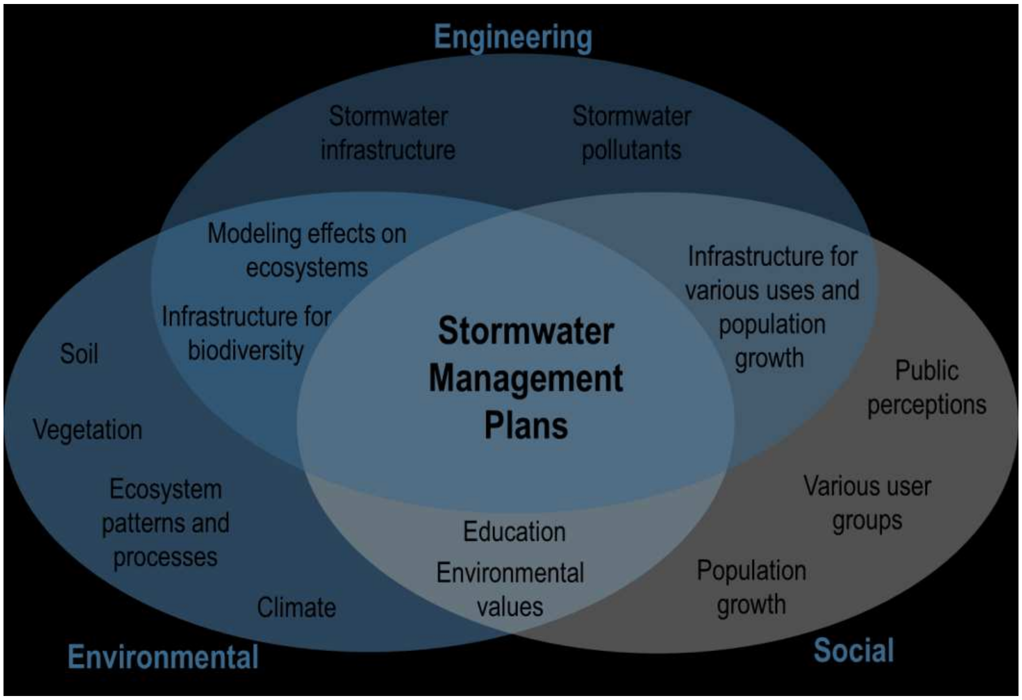

Figure 6 - Examples of engineering, environmental, and social criteria

Finally, we encourage scholars to quantify the social, economic, environmental, and policy benefits of green stormwater infrastructure so that *green stormwater management can be integrated into environment-related policy*. Stormwater governance in the U.S. is decentralized, which creates barriers from jurisdictional overlap or lack of mandate and authority in managing stormwater (Freeman 2000; Armstrong 2015; Shuster & Garmestani 2015; Chaffin et al. 2016; Dhakal & 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 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 U.S. 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 & 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 & Hahn 2015).

Acknowledgements

This research was supported by the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program (grant #R835824) and the National Science Foundation (grant #1633756).

References

Ackerman, K., 2012. Urban agriculture: Opportunities and constraints. In Metropolitan Sustainability: Understanding and Improving the Urban Environment. Urban Design Lab, The Earth Institute, Columbia University, 475 Riverside Drive, Suite 401, New York, NY 10115, United States: Elsevier Ltd., pp. 118–146.

Adyel, T.M., Oldham, C.E. & Hipsey, M.R., 2016. Stormwater nutrient attenuation in a constructed wetland with alternating surface and subsurface flow pathways: Event to annual dynamics. Water Research, 107, pp. 66–82.

Armstrong, A., 2015. Organizational adaptation in local stormwater governance / Andrea Armstrong., Logan, Utah : Utah State University.

Artita, K.S., 2012. Computer-based decision-support methods for hydrological ecosystems services management. Dissertation Abstracts International, 74(3), pp. 1-148.

Artita, K.S., Rajan, R. & Knighton, J., 2012. Seeing Green by Going Green: Maximizing Ecosystem/Community Services Benefits through Strategic Green Storm-Water Infrastructure Design. World Environmental and Water Resources Congress 2012: Crossing Boundaries, pp.520–530.

Ashley, R. et al., 2012. Accrediting surface water management systems: Natural vs proprietary. In 7th International Conference on Water Sensitive Urban Design, WSUD 2012. EcoFutures Ltd., 3 Greendale Court, Honley, Holmfirth, HD9 6JW, United Kingdom.

Attwater, R. & Derry, C., 2017. Achieving Resilience through Water Recycling in Peri-Urban Agriculture. WATER, 9(3).

Barbosa, A.E., Fernandes, J.N. & David, L.M., 2012. Key issues for sustainable urban stormwater management. Water Research, 46(20), pp.6787–6798.

Berland, A. et al., 2017. The role of trees in urban stormwater management. Landscape and Urban Planning, 162, pp.167–177.

Berland, A. & Hopton, M.E., 2014. Comparing street tree assemblages and associated stormwater benefits among communities in metropolitan Cincinnati, Ohio, USA. Urban Forestry & Urban Greening, 13(4), pp.734–741.

Bhomia, R.K., Inglett, P.W. & Reddy, K.R., 2015. Soil and phosphorus accretion rates in sub-tropical wetlands: Everglades Stormwater Treatment Areas as a case example. Science of the Total Environment, 533, pp.297–306.

Booth, E.G. et al., 2016. Is groundwater recharge always serving us well? Water supply provisioning, crop production, and flood attenuation in conflict in Wisconsin, USA. Ecosystem Services, 21(A), pp.153–165.

Bouchard, N.R. et al., 2011. Potential carbon sequestration of roadside vegetated Stormwater Control Measures (SCMs). In American Society of Agricultural and Biological Engineers Annual International Meeting 2011. NCSU, 3110 Faucette Dr., Raleigh, NC 27695, United States: American Society of Agricultural and Biological Engineers, pp. 5373–5381.

Bouchard, N.R. et al., 2013. The capacity of roadside vegetated filter strips and swales to sequester carbon. Ecological Engineering, 54, pp.227–232.

Buckland-Nicks, M., Heim, A. & Lundholm, J., 2016. Spatial environmental heterogeneity affects plant growth and thermal performance on a green roof. Science of the Total Environment,

553, pp.20–31.
Buffam, I., Mitchell, M.E. & Durtsche, R.D., 2016. Environmental drivers of seasonal variation in green roof runoff water quality. Ecological Engineering, 91, pp.506–514.
Burns, M.J. et al., 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape and Urban Planning, 105, pp.230-240
Cameron, R.W.F. & Blanusa, T., 2016. Green infrastructure and ecosystem services - is the devil in the detail? ANNALS OF BOTANY, 118(3), pp.377–391.
Carter, T. & Fowler, L., 2008. Establishing Green Roof Infrastructure Through Environmental Policy Instruments. Environmental Management, 42(1), pp.151–164.
Chaffin, B.C. et al., 2016. A tale of two rain gardens: Barriers and bridges to adaptive management of urban stormwater in Cleveland, Ohio. Journal of Environmental Management, 183(2), pp.431–441.
Chang, C.-C. et al., 2016. Sustainability. Water Environment Research, 88(10), pp.1299–1333.
Chang, C.-C. et al., 2015. Sustainability. Water Environment Research, 87(10), pp.1208–1255.
Chen, Y. et al., 2014. Influence of urban land development and subsequent soil rehabilitation on soil aggregates, carbon, and hydraulic conductivity. Science of the Total Environment, 494, pp.329–336.
Cizek, A.R., 2014. Quantifying the Stormwater Mitigation Performance and Ecosystem Service Provision in Regenerative Stormwater Conveyance (RSC). Dissertation Abstracts International. Vol. 76(7), pp.1-303
Comello, S.D. & Lepech, M.D., 2011. A framework for multiphysics modeling of natural environments for valuation of privately owned ecosystem services. IEEE International Symposium on Sustainable Systems and Technology, ISSST 2011.
Connellan, G.J., 2016. Managing plant-soil-water systems for more sustainable landscapes G. G. et al., eds. Acta Horticulturae, 1108, pp.151–158.
Connop, S. et al., 2016. Renaturing cities using a regionally-focused biodiversity-led multifunctional benefits approach to urban green infrastructure. Environmental Science & Policy, 62(SI), pp.99–111.
Coutts, C. & Hahn, M., 2015. Green Infrastructure, Ecosystem Services, and Human Health. International Journal of Environmental Research and Public Health, 12(8), pp.9768–9798.
Costanza et al., 1997.The value of the world's ecosystem services and natural capital. Nature, 387, pp.253-260.
Dagenais, D., Thomas, I. & Paquette, S., 2017. Siting green stormwater infrastructure in a neighborhood to maximize secondary benefits: lessons learned from a pilot project. Landscape Research, 42(2, SI), pp.195–210.
Davies, H.J. et al., 2017. Challenges for tree officers to enhance the provision of regulating ecosystem services from urban forests. Environmental Research, 156, pp.97–107.
Dhakal, K.P. & Chevalier, L.R., 2015. Implementing low impact development in urban landscapes: A policy perspective. In W. V.L. & K. K., eds. World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems, pp. 322–333.
Dhakal, K.P. & Chevalier, L.R., 2016. Urban Stormwater Governance: The Need for a Paradigm Shift. Environmental Management, 57(5), pp.1112–1124.

Dillon, P., Pavelic, P., et al., 2009a. Managed aquifer recharge: An Introduction. Australian National Water Commission Waterlines Report Series, 13, pp.1-65
Dillon, P., Kumar, A., et al., 2009b. Managed Aquifer Recharge -Risks to Groundwater Dependent Ecosystems -A Review Water for a Healthy Country Flagship Report to Land & Water Australia.
Doherty, J.M. et al., 2014. Hydrologic Regimes Revealed Bundles and Tradeoffs Among Six Wetland Services. Ecosystems, 17(6), pp.1026–1039.
Ebrahimian, A., Gulliver, J.S. & Wilson, B.N., 2016. Effective impervious area for runoff in urban watersheds. Hydrological Processes, 30(20), pp.3717–3729.
Elshorbagy, A., Teegavarapu, R.S.. & Ormsbee, L., 2005. Total maximum daily load (TMDL) approach to surface water quality management: concepts, issues, and applications. Canadian Journal of Civil Engineering, 32(2), pp.442–448.
English, A. & Hunt, W.F., 2009. Low impact development and permeable interlocking concrete pavements: Working with industry for material development and training offerings. 2008 International Low Impact Development Conference. Beltsville, MD.
Fleming, W.M. et al., 2014. Ecosystem services of traditional irrigation systems in northern New Mexico, USA. International Journal of Biodiversity Science, Ecosystems Services & Management, 10(4), pp.343–350.
Feng, Y. & Burian, S., 2016. Improving Evapotranspiration Mechanisms in the US Environmental Protection Agency's Storm Water Management Model. Journal of Hydrologic Engineering, 21(10).
Feng, Y., Burian, S. & Pomeroy, C., 2016. Potential of green infrastructure to restore predevelopment water budget of a semi-arid urban catchment. Journal of Hydrology, 542, pp.744–755.
Freeman, D.M., 2000. Wicked water problems: sociology and local water organizations in addressing water resources policy. Journal of the American Water Resources Association.
Gao, J. et al., 2015. Application of BMP to urban runoff control using SUSTAIN model: Case study in an industrial area. Ecological Modelling, 318(SI), pp.177–183.
Garcia-Cuerva, L., Berglund, E.Z. & Rivers, L., 2016. Exploring Strategies for LID Implementation in Marginalized Communities and Urbanizing Watersheds. In R. D. & P. C.S., eds. 16th World Environmental and Water Resources Congress 2016: Water, Wastewater, and Stormwater and Urban Watershed Symposium. pp. 41–50.
Ghermandi, A., 2016. Analysis of intensity and spatial patterns of public use in natural treatment systems using geotagged photos from social media. Water Research, 105, pp.297–304.
Gittleman, M. et al., 2017. Estimating stormwater runoff for community gardens in New York City. Urban Ecosystems, 20(1), pp.129–139.
Greenway, M., 2015. Stormwater wetlands for the enhancement of environmental ecosystem services: Case studies for two retrofit wetlands in Brisbane, Australia. Journal of Cleaner Production, pp. 1-10
Griffin, M.P. et al., 2014. Storm-event flow pathways in lower coastal plain forested watersheds of the southeastern United States. Water Resources Research, 50(10), pp.8265–8280.
Gruwald, L. et al., 2017. A GIS-based mapping methodology of urban green roof ecosystem

services applied to a Central European city. Urban Forestry & Urban Greening, 22, pp.54–63.

Guertin, D.P. et al., 2015. Evaluation of Green Infrastructure Designs Using the Automated Geospatial Watershed Assessment Tool. In M. G.E., ed. 11th Watershed Management Symposium 2015: Power of the Watershed. School of Natural Resources and the Environment, pp. 229–239.

Gulf Coast Ecosystem Restoration Task Force, 2012. Gulf of Mexico regional ecosystem restoration strategy. In Gulf Coast Ecosystem Restoration Strategy and Long-Term Recovery Plan. Nova Science Publishers, Inc., pp. 1–119.

Hale, R.L. et al., 2015. iSAW: Integrating Structure, Actors, and Water to study socio-hydro-ecological systems. Earth's Future, 3, pp.110-132.

Hamel, P., Daly, E. & Fletcher, T.D., 2013. Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. Journal of Hydrology, 485, pp.201–211.

Hassall, C., 2014. The ecology and biodiversity of urban ponds. Wiley Interdisciplinary Reviews; Water, 1(2), pp.187–206.

Hassall, C. & Anderson, S., 2015. Stormwater ponds can contain comparable biodiversity to unmanaged wetlands in urban areas. Hydrobiologia, 745(1), pp.137–149.

Haukos, D.A. et al., 2016. Effectiveness of vegetation buffers surrounding playa wetlands at contaminant and sediment amelioration. Journal of Environmental Management, 181, pp.552–562.

Heim, A. & Lundholm, J., 2016. Phenological complementarity in plant growth and reproduction in a green roof ecosystem. Ecological Engineering, 94, pp.82–87.

Heim, A., Lundholm, J. & Philip, L., 2014. The impact of mosses on the growth of neighbouring vascular plants, substrate temperature and evapotranspiration on an extensive green roof. Urban Ecosystems, 17(4), pp.1119–1133.

Heintzman, L.J. et al., 2015. Local and landscape influences on PAH contamination in urban stormwater. Landscape And Urban Planning, 142(SI), pp.29–37.

Herrmann, D.L., Shuster, W.D. & Garmestani, A.S., 2017. Vacant urban lot soils and their potential to support ecosystem services. Plant And Soil, 413(1–2), pp.45–57.

Hoang, L. & Fenner, R.A., 2016. System interactions of stormwater management using sustainable urban drainage systems and green infrastructure. Urban Water Journal, 13(7), pp.739–758.

Hobbie, S.E. et al., 2017. Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. Proceedings of The National Academy Of Sciences Of The United States Of America, 114(16), pp.4177–4182.

Hogan, D.M. & Walbridge, M.R., 2007. Urbanization and nutrient retention in freshwater riparian wetlands. Ecological Applications, 17(4), pp.1142–1155.

Horsley, S., Perry, E. & Counsell, L., 2016. Three Bays Estuary (Barnstable, Cape Cod) Watershed Restoration Plan: A Green Infrastructure Approach. Journal of Green Building, 11(2), pp.22–38.

Hoss, F., Fischbach, J. & Molina-Perez, E., 2016. Effectiveness of Best Management Practices for Stormwater Treatment as a Function of Runoff Volume. Journal of Water Resources

Planning and Management, 142(11).
Isely, E.S. et al., 2014. Building partnerships to address conservation and management of western Michigan's natural resources. Freshwater Science, 33(2), pp.679–685.
Ishimatsu, K. et al., 2017. Use of rain gardens for stormwater management in urban design and planning. Landscape And Ecological Engineering, 13(1), pp.205–212.
Jaffe, M., 2010. Reflections on green infrastructure economics. Environmental Practice, 12(4), pp.357–365.
Johnson, T., Lawry, D. & Sapdhare, H., 2016. The Council verge as the next wetland: TREENET and the cities of Mitcham and Salisbury investigate G. G. et al., eds. Acta Horticulture, 1108, pp.63–70.
Kabbes, K.C. & Windhager, S., 2010. Sustainable site initiative - Protecting and restoring site ecosystem services. In World Environmental and Water Resources Congress 2010: Challenges of Change. Kabbes Engineering, Inc., 1250 S. Grove Ave. #304, Barrington, IL 60010, United States, pp. 4086–4092.
Kandulu, J.M., Connor, J.D. & MacDonald, D.H., 2014. Ecosystem services in urban water investment. Journal Of Environmental Management, 145, pp.43–53.
Kandulu, J.M. et al., 2017. Ecosystem Service Impacts of Urban Water Supply and Demand Management. Water Resources Management, pp.1–15.
Kati, V. & Jari, N., 2016. Bottom-up thinking Identifying socio-cultural values of ecosystem services in local blue-green infrastructure planning in Helsinki, Finland. Land Use Policy, 50, pp.537–547.
Kaushal, S.S., McDowell, W.H. & Wollheim, W.M., 2014. Tracking evolution of urban biogeochemical cycles: past, present, and future. Biogeochemistry, 121(1), pp.1–21.
Keeley, M. et al., 2013. Perspectives on the use of green infrastructure for stormwater management in Cleveland and Milwaukee. Environmental Management, 51, pp.1093-1108
Kellogg, W. & Matheny, E., 2006. Training opportunities available to Ohio Lake Erie basin local decision-makers regarding the economic and fiscal benefits of coastal and watershed stewardship. Journal Of Great Lakes Research, 32(1), pp.142–157.
Klimas, C. et al., 2016. Valuing Ecosystem Services and Disservices across Heterogeneous Green Spaces. Sustainability, 8(9).
Knowles, N., Dettinger, M.D. & Cayan, D.R., 2006. Trends in Snowfall versus Rainfall in the Western United States. Journal of Climate, 19(18), pp.4545–4559.
Kopecka, M. et al., 2017. Analysis of urban green spaces based on sentinel-2A: Case studies from Slovakia†. Land, 6(2).
Kopperoinen, L., Itkonen, P. & Niemela, J., 2014. Using expert knowledge in combining green infrastructure and ecosystem services in land use planning: an insight into a new place-based methodology. Landscape Ecology, 29(8), pp.1361–1375.
Kremer, P., Hamstead, Z.A. & McPhearson, T., 2015. The value of urban ecosystem services in New York City: A spatially explicit multicriteria analysis of landscape scale valuation scenarios. Environmental Science and Policy, 62(SI), pp.57–68.
Kubasek, N.K. & Silverman, G.S., 2005. Environmental Law Fifth., Upper Saddle River, New Jersey: Pearson Prentice Hall.
Kuller, M. et al., 2017. Framing water sensitive urban design as part of the urban form: A critical

review of tools for best planning practice. Environmental Modelling & Software, 96, pp.265–282.
Kumar, K. & Hundal, L.S., 2016. Soil in the city: Sustainably improving urban soils. Journal of Environmental Quality, 45(1), pp.2–8.
Kuoppamaki, K. et al., 2016. Biochar amendment in the green roof substrate affects runoff quality and quantity. Ecological Engineering, 88, pp.1–9.
Lapointe, B.E. & Bedford, B.J., 2011. Stormwater nutrient inputs favor growth of non-native macroalgae (Rhodophyta) on O'ahu, Hawaiian Islands. Harmful Algae, 10(3), pp.310–318.
Larson, E.K., 2010. Water and nitrogen in designed ecosystems: Biogeochemical and economic consequences. Dissertation Abstracts International, 72(2), pp. 1-275.
Lawson, E. et al., 2014. Delivering And Evaluating The Multiple Flood Risk Benefits In Blue-Green Cities: An Interdisciplinary Approach. WIT Transactions on Ecology and the Environment, 184.
Ligare, S.T., Viers, J.H., Null, S.E., Rheinheimer, D., & Mount, J.F. 2012. Non-uniform changes to whitewater recreation in California's Sierra Nevada from regional climate warming. River Research and Applications, 28: 1299-1311.
Livesley, S.J., McPherson, G.M. & Calfapietra, C., 2016. The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale. Journal of Environmental Quality, 45(1), pp.119–124.
Londono Cadavid, C. & Ando, A.W., 2013. Valuing preferences over stormwater management outcomes including improved hydrologic function. Water Resources Research, 49(7), pp.4114–4125.
Lovell, S.T. & Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landscape Ecology, 28(8), pp.1447–1463.
Lundholm, J. et al., 2010. Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions. Plos One, 5(3).
Lundholm, J.T., 2015. Green roof plant species diversity improves ecosystem multifunctionality. Journal Of Applied Ecology, 52(3), pp.726–734.
Lundy, L. & Wade, R., 2011. Integrating sciences to sustain urban ecosystem services. Progress In Physical Geography, 35(5, SI), pp.653–669.
MacDonald, D.H. et al., 2015. Valuing coastal water quality: Adelaide, South Australia metropolitan area. Marine Policy, 52, pp.116–124.
McDonald, R.I., 2015. The effectiveness of conservation interventions to overcome the urban-environmental paradox. Annals of the New York Academy of Sciences, 1355(1), pp.1–14.
MacIvor, J.S. et al., 2016. Phylogenetic ecology and the greening of cities. Journal Of Applied Ecology, 53(5), pp.1470–1476.
Maillard, E. & Imfeld, G., 2014. Pesticide Mass Budget in a Stormwater Wetland. Environmental Science & Technology, 48(15, SI), pp.8603–8611.
Maliva, R.G., 2014. Economics of managed aquifer recharge. Water (Switzerland).
Mayer, A.L. et al., 2012. Building green infrastructure via citizen participation: A six-year study in the Shepherd Creek (Ohio). Environmental Practice, 14(1), pp.57–67.
Mazzotta, M.J., Besedin, E. & Speers, A.E., 2014. A Meta-Analysis of Hedonic Studies to Assess the Property Value Effects of Low Impact Development. Resources, 3(1), pp.31–61.

McDonough, K., Moore, T. & Hutchinson, S., 2017. Understanding the Relationship between Stormwater Control Measures and Ecosystem Services in an Urban Watershed. Journal of Water Resources Planning And Management, 143(5).

McDonough, K.R., Moore, T. & Hutchinson, S., 2016. Evaluating urban best management practices as a tool for the provision of hydrologic ecosystem services. 2016 ASABE Annual International Meeting.

McDuffie, E. et al., 2015. A study of ecosystem services provided by a storm water retrofit system on a public school campus in Orange County, North Carolina. Sustainability (United States), 8(2), pp.85–94.

McPhearson, T. et al., 2013. Local assessment of New York City: Biodiversity, green space, and ecosystem services. In Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities: A Global Assessment. Tishman Environment and Design Center, Springer Netherlands, pp. 335–383.

McPhearson, T., Hamstead, Z.A. & Kremer, P., 2014. Urban Ecosystem Services for Resilience Planning and Management in New York City. AMBIO, 43(4, SI), pp.502–515.

McPherson, E.G. et al., 2011. Million trees Los Angeles canopy cover and benefit assessment. Landscape and Urban Planning, 99(1), pp.40–50.

Meerow, S. & Newell, J.P., 2017. Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. Landscape and Urban Planning, 159, pp.62–75.

Merriman, L.S. et al., 2017. Evaluation of factors affecting soil carbon sequestration services of stormwater wet retention ponds in varying climate zones. Science of the Total Environment, 583, pp.133–141.

Merriman, L.S. & Hunt, W.F., 2012. Assessing the development of ecosystem services in constructed stormwater wetlands. In American Society of Agricultural and Biological Engineers Annual International Meeting (ASABE) 2012, pp. 2408–2414.

Merriman, L.S., Hunt, W.F. & Bass, K.L., 2016. Development/ripening of ecosystems services in the first two growing seasons of a regional-scale constructed stormwater wetland on the coast of North Carolina. Ecological Engineering, 94, pp.393–405.

Mitsova, D., Shuster, W. & Wang, X., 2011. A cellular automata model of land cover change to integrate urban growth with open space conservation. Landscape and Urban Planning, 99(2), pp.141–153.

Mogollon, B. et al., 2016. Mapping technological and biophysical capacities of watersheds to regulate floods. Ecological Indicators, 61(2), pp.483–499.

Moll, G., 2005. Repairing ecosystems at home. American Forests, 111(2), pp.41–44.

Monaghan, P. et al., 2016. Balancing the Ecological Function of Residential Stormwater Ponds with Homeowner Landscaping Practices. Environmental Management, 58(5), pp.843–856.

Moore, T.L.C. & Hunt, W.F., 2012. Ecosystem service provision by stormwater wetlands and ponds – A means for evaluation? Water Research, 46(20), pp.6811–6823.

Moore, T.L.C. & Hunt, W.F., 2011. Stormwater ponds and wetlands: Beyond runoff regulation. In American Society of Agricultural and Biological Engineers Annual International Meeting 2011. North Carolina State University, Campus Box 7625, Raleigh, NC 27695, United States: American Society of Agricultural and Biological Engineers, pp. 1245–1258.

Moyles, C. & Craul, T., 2016. Scenic Hudson's Long Dock Park Cultivating Resilience:

Transforming a Post-Industrial Brownfield into a Functional Ecosystem. Journal of Green Building, 11(3), pp.55–77.
Nasirian, H. et al., 2016. Assessment of bed sediment metal contamination in the Shadegan and Hawr Al Azim wetlands, Iran. Environmental Monitoring and Assessment, 188(2).
Natarajan, P. & Davis, A.P., 2016. Ecological assessment of a transitioned stormwater infiltration basin. Ecological Engineering, 90, pp.261–267.
Nigussie, T.A. & Altunkaynak, A., 2016. Modeling Urbanization of Istanbul under Different Scenarios Using SLEUTH Urban Growth Model. Journal of Urban Planning and Development.
Nocco, M.A., Rouse, S.E. & Balster, N.J., 2016. Vegetation type alters water and nitrogen budgets in a controlled, replicated experiment on residential-sized rain gardens planted with prairie, shrub, and turfgrass. Urban Ecosystems, 19(4), pp.1665–1691.
Null, S.E. & Prudencio, L., 2016. Climate change effects on water allocations with season dependent water rights. Science of the Total Environment, 571.
Null, S.E. & Viers, J.H., 2013. In bad waters: Water year classification in nonstationary climates. Water Resources Research, 49(2), pp.1137–1148.
Oberndorfer, E. et al., 2007. Green roofs as urban ecosystems: Ecological structures, functions, and services. Bioscience, 57(10), pp.823–833.
O'Sullivan, O.S. et al., 2017. Optimising UK urban road verge contributions to biodiversity and ecosystem services with cost-effective management. Journal of Environmental Management, 191, pp.162–171.
Oldfield, E.E. et al., 2013. FORUM: Challenges and future directions in urban afforestation. Journal of Applied Ecology, 50(5), pp.1169–1177.
Olguin, E.J. et al., 2017. Long-term assessment at field scale of Floating Treatment Wetlands for improvement of water quality and provision of ecosystem services in a eutrophic urban pond. Science of the Total Environment, 584, pp.561–571.
Palmer, M.A., Filoso, S. & Fanelli, R.M., 2014. From ecosystems to ecosystem services: Stream restoration as ecological engineering. Ecological Engineering, 65, pp.62–70.
Palta, M.M., 2012. Denitrification in urban brownfield wetlands. Dissertation Abstracts International. 73(164), pp. 1-164.
Pappalardo, V. et al., 2017. The potential of green infrastructure application in urban runoff control for land use planning: A preliminary evaluation from a southern Italy case study. Ecosystem Services, 26, pp.345–354.
Pataki, D.E. et al., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Frontiers in Ecology and the Environment, 9(1, SI), pp.27–36.
Perales-Momparler, S. et al., 2015. A regenerative urban stormwater management methodology: the journey of a Mediterranean city. Journal of Cleaner Production, 109(SI), pp.174–189.
Pyke, C. et al., 2011. Assessment of low impact development for managing stormwater with changing precipitation due to climate change. Landscape and Urban Planning, 103(2), pp.166–173.
Qiu, Z., Dosskey, M.G. & Kang, Y., 2016. Choosing between alternative placement strategies for

conservation buffers using Borda count. Landscape and Urban Planning, 153, pp.66–73.
Reistetter, J.A. & Russell, M., 2011. High-resolution land cover datasets, composite curve numbers, and storm water retention in the Tampa Bay, FL region. Applied Geography, 31(2), pp.740–747.
Rhea, L. et al., 2014. Data proxies for assessment of urban soil suitability to support green infrastructure. Journal of Soil and Water Conservation, 69(3), pp.254–265.
Rheinheimer, D.E., Null, S.E. & Viers, J.H., 2016. Climate-Adaptive Water Year Typing for Instream Flow Requirements in California's Sierra Nevada. Journal of Water Resources Planning and Management.
Rogers, J., 2013. Green, Brown or Grey: Green Roofs As "sustainable" Infrastructure. WIT Transactions on Ecology and the Environment, 173.
Rooney, R.C. et al., 2015. Replacing natural wetlands with stormwater management facilities: Biophysical and perceived social values. Water Research, 73, pp.17–28.
Roy, A.H. et al., 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: Lessons from Australia and the United States. Environmental Management, 32, pp.344-359.
Rozos, E., Makropoulos, C. & Maksimovic, C., 2013. Rethinking urban areas: an example of an integrated blue-green approach. Water Science and Technology-Water Supply, 13(6), pp.1534–1542.
Rumble, H. & Gange, A.C., 2017. Microbial inoculants as a soil remediation tool for extensive green roofs. Ecological Engineering, 102, pp.188–198.
Russo, A. et al., 2017. Edible green infrastructure: An approach and review of provisioning ecosystem services and disservices in urban environments. Agriculture Ecosystems & Environment, 242, pp.53–66.
Schuch, G. et al., 2017. Water in the city: Green open spaces, land use planning and flood management - An Australian case study. Land Use Policy, 63, pp.539–550.
Sharley, D.J. et al., 2016. Detecting long-term temporal trends in sediment-bound trace metals from urbanised catchments. Environmental Pollution, 219, pp.705–713.
Shuster, W.D. et al., 2014. Residential demolition and its impact on vacant lot hydrology: Implications for the management of stormwater and sewer system overflows. Landscape And Urban Planning, 125(SI), pp.48–56.
Shuster, W.D. & Garmestani, A.S., 2015. Adaptive exchange of capitals in urban water resources management: an approach to sustainability? Clean Technologies And Environmental Policy, 17(6), pp.1393–1400.
Shuster, W.D., Gehring, R. & Gerken, J., 2007. Prospects for enhanced groundwater recharge via infiltration of urban storm water runoff: A case study. Journal Of Soil And Water Conservation, 62(3), pp.129–137.
Sjöman, H. et al., 2015. Herbaceous plants for climate adaptation and intensely developed urban sites in northern Europe: A case study from the eastern Romanian steppe. Ekologia Bratislava, 34(1), pp.39–53.
Soares, A.L. et al., 2011. Benefits and costs of street trees in Lisbon, Portugal. Urban Forestry and Urban Greening, 10(2), pp.69–78.
Soberg, L.C. et al., 2016. Bioaccumulation of heavy metals in two wet retention ponds. Urban

Water Journal, 13(7), pp.697–709.
Squier, M.N. et al., 2014. Preliminary heat transfer analysis for a large extensive green roof. In H. C., C. J., & W. B., eds. 2014 International Conference on Sustainable Infrastructure: Creating Infrastructure for a Sustainable World, ICSI 2014. Department of Civil and Environmental Engineering, Syracuse University, 151 Link Hall, Syracuse, NY, United States: American Society of Civil Engineers (ASCE), pp. 1077–1085.
Staley, D.C., 2015. Urban forests and solar power generation: partners in urban heat island mitigation. International Journal of Low-Carbon Technologies, 10(1, SI), pp.78–86.
Starry, O. et al., 2011. Utilizing sensor networks to assess evapotranspiration by greenroofs. American Society of Agricultural and Biological Engineers Annual International Meeting 2011, pp. 229–235.
Stephens, D.B. et al., 2012. Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff1. JAWRA Journal of the American Water Resources Association, 48(1), pp.134–144.
Taylor, J.R. & Lovell, S.T., 2014. Urban home food gardens in the Global North: research traditions and future directions. Agriculture and Human Values, 31(2), pp.285–305.
Thornton, P.K. et al., 2014. Climate variability and vulnerability to climate change: a review. Global Change Biology, 20(11), pp.3313–3328.
Tilley, D.R. & Brown, M.T., 2006. Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems. Ecological Modelling, 192(3–4), pp.327–361.
Tsihrintzis, V.A. & Hamid, R., 1997. Modeling and Management of Urban Stormwater Runoff Quality: A Review. Water Resources Management, 11, pp.137–164.
Tzankova, Z., 2013. The Difficult Problem of Nonpoint Nutrient Pollution: Could The Endangered Species Act Offer Some Relief? William & Mary Environmental Law & Policy Review, 37(3), pp.709–757.
Ursino, N. & Grisi, A., 2017. Reliability and efficiency of rainwater harvesting systems under different climatic and operational scenarios. International Journal of Sustainable Development and Planning, 12(1), pp.194–199.
Uzomah, V., Scholz, M. & Almuktar, S., 2014. Rapid expert tool for different professions based on estimated ecosystem variables for retrofitting of drainage systems. Computers Environment And Urban Systems, 44, pp.1–14.
Van Stan II, J.T., Levia Jr., D.F. & Jenkins, R.B., 2015. Forest Canopy Interception Loss Across Temporal Scales: Implications for Urban Greening Initiatives. Professional Geographer, 67(1), pp.41–51.
Verbeeck, K. et al., 2014. Infiltrating into the paved garden - a functional evaluation of parcel imperviousness in terms of water retention efficiency. Journal of Environmental Planning and Management, 57(10), pp.1552–1571.
Vogel, J.R. et al., 2015. Critical Review of Technical Questions Facing Low Impact Development and Green Infrastructure: A Perspective from the Great Plains. Water Environment Research, 87(9, SI), pp.849–862.
Volder, A. & Dvorak, B., 2014. Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas.

Sustainable Cities and Society, 10, pp.59–64.
Voskamp, I.M. & de Ven, F.H.M., 2015. Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. Building and Environment, 83(SI), pp.159–167.
Walker, L. et al., 2012. Surface water management and urban green infrastructure in the UK: A review of benefits and challenges. 7th International Conference on Water Sensitive Urban Design (WSUD), 2012, EcoFutures Ltd.
Waltham, N.J. et al., 2014. Protecting the Green Behind the Gold: Catchment-Wide Restoration Efforts Necessary to Achieve Nutrient and Sediment Load Reduction Targets in Gold Coast City, Australia. Environmental Management, 54(4), pp.840–851.
Waltham, N.J. et al., 2014. Water and sediment quality, nutrient biochemistry and pollution loads in an urban freshwater lake: balancing human and ecological services. Environmental Science-Processes & Impacts, 16(12), pp.2804–2813.
Ward, E.W. & Winter, K., 2016. Missing the link: urban stormwater quality and resident behavior. Water S. A., 42(4), p.571.
Wardynski, B.J., Winston, R.J. & Hunt, W.F., 2012. Internal Water Storage Enhances Exfiltration and Thermal Load Reduction from Permeable Pavement in the North Carolina Mountains. Journal of Environmental Engineering-Asce, 139(2), pp.187–195.
Walsh, C.J. et al., 2016. Principles for urban stormwater management to protect stream ecosystems. Urban Streams Perspectives, 35(1), pp.398–411.
Welsh, J.T. & Mooney, P., 2014. The St George Rainway: Building Community Resilience with Green Infrastructure. WIT Transactions on the Built Environment, 139.
Widney, S., Fischer, B.C. & Vogt, J., 2016. Tree Mortality Undercuts Ability of Tree-Planting Programs to Provide Benefits: Results of a Three-City Study. Forests, 7(3).
Williams, M.R., Wessel, B.M. & Filoso, S., 2016. Sources of iron (Fe) and factors regulating the development of flocculate from Fe-oxidizing bacteria in regenerative streamwater conveyance structures. Ecological Engineering, 95, pp.723–737.
Wilson, L.I., 2012. Attitudes Towards Ecosystem Services in Urban Riparian Parks. Masters Abstracts International, 51(2), pp.1-130.
Winston, R.J., Bouchard, N.R. & Hunt, W.F., 2013. Carbon sequestration by roadside filter strips and swales: A field study. In 2nd Green Streets, Highways, and Development Conference 2013: Advancing the Practice. Department of Biological and Agricultural Engineering, North Carolina State University, Campus Box 7625, Raleigh, NC 27695-7625, United States, pp. 355–367.
Wolf, D. & Lundholm, J.T., 2008. Water uptake in green roof microcosms: Effects of plant species and water availability. Ecological Engineering, 33(2), pp.179–186.
Wolf, K.L. & Robbins, A.S., 2015. Metro nature, environmental health, and economic value. Environmental Health Perspectives, 123(5), pp.390–398.
Wong, G.K.L. & Jim, C.Y., 2015. Identifying keystone meteorological factors of green-roof stormwater retention to inform design and planning. Landscape and Urban Planning, 143, pp.173–182.
Wu, J.Y. et al., 2013. Using the Storm Water Management Model to predict urban headwater stream hydrological response to climate and land cover change. Hydrology and Earth

System Sciences, 17(12), pp.4743–4758.
Xue, X. et al., 2015. Critical insights for a sustainability framework to address integrated community water services: Technical metrics and approaches. Water Research, 77, pp.155–169.
Yadav, P. et al., 2012. Factors affecting mosquito populations in created wetlands in urban landscapes. Urban Ecosystems, 15(2), pp.499–511.
Yang, B. et al., 2015. Green Infrastructure Design for Improving Stormwater Quality: Daybreak Community in the United States West. Landscape Architecture Frontiers, 3(4).
Yang, B., Li, M.-H. & Li, S., 2013. Design-with-Nature for Multifunctional Landscapes: Environmental Benefits and Social Barriers in Community Development. International Journal of Environmental Research and Public Health, 10(11), pp.5433–5458.
Yang, B. & Li, S., 2016. Design with Nature: Ian McHarg's ecological wisdom as actionable and practical knowledge. Landscape and Urban Planning, 155(SI), pp.21–32.
Yang, L. et al., 2015. Water-related ecosystem services provided by urban green space: A case study in Yixing City (China). Landscape and Urban Planning, 136, pp.40–51.
Yeoman, K., Jiang, B. & Mitsch, W.J., 2017. Phosphorus concentrations in a Florida Everglades water conservation area before and after El Niño events in the dry season. Ecological Engineering.
Zhang, W. et al., 2015. Reclaimed Water Systems: Biodiversity Friend or Foe? L. B.G. et al., eds. ACS Symposium Series, 1206, pp.355–374.
Zhang, Z. et al., 2012. Wetland Network Design for Mitigation of Saltwater Intrusion by Replenishing Freshwater in an Estuary. Clean-Soil Air Water, 40(10, SI), pp.1036–1046.
Zhou, L. et al., 2017. Ecological and economic impacts of green roofs and permeable pavements at the city level: the case of Corvallis, Oregon. Journal of Environmental Planning and Management, pp.1–21.
Zimmermann, E. et al., 2016. Urban Flood Risk Reduction by Increasing Green Areas for Adaptation to Climate Change. In S. C., A. M., & P. P., eds. World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium, WMCAUS 2016. Hydraulic Department. Fac. Ex. Sc., Eng. Nat. University of Rosario. CONICET, Rosario, Argentina: Elsevier Ltd, pp. 2241–2246.
Zölch, T. et al., 2017. Regulating urban surface runoff through nature-based solutions - An assessment at the micro-scale. Environmental Research, 157, pp.135–144.