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Arid Green Infrastructure for Water Control and Conservation:

State of the Science and Research Needs for Arid/Semi-Arid Regions

RESEARCH AND DEVELOPMENT

Arid Green Infrastructure for Water Control and Conservation

State of the Science and Research Needs for Arid/Semi-Arid Regions

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by

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Abstract

Green infrastructure is an approach to managing wet weather flows using systems and practices that mimic natural processes. It is designed to manage stormwater as close to its source as possible and protect the quality of receiving waters. Although most green infrastructure practices were first developed in temperate climates, green infrastructure also can be a cost-effective approach to stormwater management and water conservation in arid and semi-arid regions, such as those found in the western and southwestern United States. Green infrastructure practices can be applied at the site, neighborhood and watershed scales. In addition to water management and conservation, implementing green infrastructure confers many social and economic benefits and can address issues of environmental justice.

The U.S. Environmental Protection Agency (EPA) provides strong support for and promotes the benefits of using green infrastructure in protecting drinking water supplies and public health, mitigating overflows from combined and separate sewers, and reducing stormwater pollution. EPA has developed tools and resources to guide the design, implementation and maintenance of green infrastructure best management practices (BMPs) and has issued guidance to encourage the use of green infrastructure to help manage stormwater. As a member of the Green Infrastructure Collaborative, EPA also actively partners with federal and nonfederal organizations to foster the adoption of green infrastructure. EPA regional offices in the West and Southwest also take an active role in fostering adoption of green infrastructure BMPs within their regions.

Addressing drought and water sustainability through green infrastructure is the subject of policy initiatives and guidance at the federal, state and local levels. Increasing the use of green infrastructure to manage stormwater is one of the goals of Executive Order 13693, *Planning for Federal Sustainability in the Next Decade*. Arizona, Washington and Texas all have issued guidance on the use of green infrastructure to manage or conserve stormwater. In addition, municipalities and counties located in arid and semi-arid climate regions provide guidance on green infrastructure design and implementation tailored to local conditions, including local climate, topography, hydrology and soil types. Citizens also have taken an active role in promoting and executing the adoption of green infrastructure in their local communities.

A survey of current literature was conducted to characterize the current state of the science for the application of green infrastructure to arid and semi-arid climates and to identify future research opportunities. Stormwater management BMPs (e.g., bioswales; green roofs; permeable pavement; planter boxes; rain gardens/bioretention cells; vegetated filter strips; integrated, multi-

BMP systems; land conservation; riparian buffers; urban tree canopies) have been evaluated in arid, semi-arid and Mediterranean climates for management of stormwater quantity and quality. Practices have been tested for their ability to improve the water quality of stormwater and to sequester carbon and nitrogen. For practices that use soil substrates, leaching of nutrients and other pollutants has been quantified. The ability of BMPs to reduce runoff is a key performance parameter that has been evaluated under different precipitation regimes. Optimal BMP design and maintenance needs—primarily irrigation—for arid and semi-arid regions have been explored. BMP siting considerations and approaches have been studied, primarily on a watershed scale. Research also has been conducted relevant to the use of green infrastructure to conserve water in arid and semi-arid regions of the United States. Studies have assessed the effectiveness of different types of in-field rainwater harvesting systems in increasing agricultural productivity and of roof-top water harvesting systems in meeting nonpotable domestic water needs, including indoor use and landscape irrigation. Possible impacts of rainwater harvesting on the local water balance have been evaluated. Design elements to maximize effectiveness of rainwater harvesting practices also have been studied.

EPA supports an active intramural and extramural research program on green infrastructure practices. Researchers and stakeholders have identified arid green infrastructure research opportunities that are relevant to EPA's mission. Stakeholders who participated in a workshop sponsored by AridLID.org identified the following research and data needs for EPA to address: a review of institutions' codes and ordinances for treating soil as a resource; a database of existing findings; a process for prioritizing projects within a watershed; and the research topics of pretreatment and treatment needs before infiltration, plant/soil interactions and pollutant removal, the impact of green infrastructure/low-impact development (LID) on flood frequency and volume, the impact of green infrastructure/LID on floods as a downstream resource, and ground water impacts resulting from water infiltration.

Researchers in the surveyed literature recommend support for further research at the site scale on the following topics: replicating field studies; investigating the mechanisms behind effects on stormwater quality; optimizing design criteria; exploring sustainable solutions to irrigation needs; improving models of effectiveness by refining model parameters, validating models with field studies, conducting sensitivity and uncertainty analyses, and incorporating high-resolution data; developing a better understanding of maintenance needs; and optimizing siting of BMPs. On a watershed scale, researchers recommend prioritizing sites for installing BMPs, assessing economic viability, replicating results in other locations, incorporating high-resolution data in models, improving the mechanistic understanding of biogeochemical processes, gathering more environmental data relevant to successful installation of practices, and improving model parameterization. For stormwater conservation research, support is needed for replicating research studies under a variety of conditions, including geography, climate, soil type and hydrology; conducting more systematic and comparable studies; and evaluating the cost-effectiveness of BMPs at a variety of scales.

Further research on effectiveness is needed in general for some of the common BMPs. In addition, the field would benefit from more research on maintenance, research at longer timescales and larger geographic scales, refinement of models of arid and semi-arid conditions, and more research conducted within the United States under locally relevant conditions. Such investigations would facilitate the use of green infrastructure to meet stormwater regulatory goals.

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Acronyms and Abbreviations

BMP	best management practice
CEQ	Council on Environmental Quality
COD	chemical oxygen demand
CSO	combined sewer overflow
DEM	digital elevation model
DOC	dissolved organic carbon
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
EO	Executive Order
FAO	Food and Agriculture Organization
GIS	geographic information system
LID	low-impact development
LiDAR	light detection and ranging
LTCP-EZ	Long-Term Control Plan-EZ
MS4	Municipal Separate Storm Sewer System
NCAT	National Center for Asphalt Technology
NPDES	National Pollutant Discharge Elimination System
NRCS	Natural Resources Conservation Service
ORD	Office of Research and Development
PAH	polycyclic aromatic hydrocarbon
SWAT	Soil and Water Assessment Tool
SWMM	Storm Water Management Model
TKN	total Kjeldahl nitrogen
TMDL	total maximum daily load
TSS	total suspended solids
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

Chapter 1.

Introduction

The U.S. Environmental Protection Agency (EPA) commissioned a literature review to identify the state-of-the science practices dealing with water control and conservation in arid and semi-arid regions, with emphasis on these regions in the United States. The search focused on stormwater control measures or practices that slow, capture, treat, infiltrate and/or store runoff at its source (i.e., green infrastructure). The material in Chapters 1 through 3 provides background to EPA's current activities related to the application of green infrastructure practices in arid and semi-arid regions. An introduction to the topic of green infrastructure in arid and semi-arid regions is presented in Chapter 1, including definitions of terms used in this document; descriptions of green infrastructure practices applicable to arid and semi-arid regions, both in developed and developing countries; benefits of green infrastructure in arid and semi-arid regions; and unique aspects of green infrastructure in arid and semi-arid regions of the United States. Chapter 2 focuses on green infrastructure resources that have been developed by EPA at the program and regional office level. Policy initiatives and guidance to address drought and water sustainability through green infrastructure in arid and semi-arid regions of the United States that have been formulated at the state, regional and municipal/county levels, as well as by nongovernmental agencies and collaboratively, are presented in Chapter 3. Chapter 3 also includes federal actions related to green infrastructure that apply across the United States. Chapter 4 presents the results of the literature review, organized by practice. Based on the research needs identified in the literature, as well as topics identified by experts in a recent conference focused on developing a research agenda, areas of research for applying green infrastructure in arid and semi-arid regions that are relevant to EPA's mission are presented in Chapter 5. Varying levels of detail on different practices are available in the literature, which is reflected in Chapters 4 and 5. Chapter 6 is a summary of the findings of the literature review.

1.1. Definitions of low-impact development and green infrastructure

EPA defines low-impact development (LID) as "systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater in order to protect water quality and associated aquatic habitat." Development or re-development using the LID approach involves managing stormwater as close to its source as possible (USEPA 2016).

Green infrastructure as defined by EPA refers to managing wet weather flows using LID practices (USEPA 2016i). Green infrastructure is contrasted with conventional gray stormwater infrastructure, which is designed to move stormwater away from the built environment. In urban areas, green infrastructure "uses vegetation, soils, and other elements and practices to restore some of the natural processes required to manage water and create healthier urban environments." Traditional stormwater management practices (i.e., so-called "gray infrastructure"), such as separate storm sewers and concrete river channels, in contrast, are designed to transport stormwater away from its source. Green infrastructure elements and practices can be applied at the site, neighborhood, city and county scales (USEPA 2015s).

1.2. Definitions of arid and semi-arid climate types

Deserts are arid regions that support limited vegetation. The most widely used climate classification system is the Köppen-Geiger classification system, as updated by Peel, Finlayson and Mcmahon (2007), which is derived from data on the mean annual precipitation, mean annual temperature and seasonality of precipitation. Climate type Group B is arid, with subtypes indicating arid (W) or steppe (i.e., semi-arid, S) and hot (h) or cold (k). Mediterranean climates (Köppen-Geiger climate symbols Csa and Csb) are temperate with hot, dry summers. With respect to vegetation, dry climates can be divided into arid and semi-arid based on the ratio between annual precipitation and potential evapotranspiration rate (the aridity index), which is a measure of the adequacy of moisture relative to the needs of plants and is estimated as a function of precipitation, temperature and other factors (Meigs 1953; Thornthwaite 1948). The general term "xeric" is used in this document to refer to arid and semi-arid, as well as seasonally dry, climates.

1.2.1. Geographic distribution of arid and semi-arid regions

Deserts comprise approximately one-third of the Earth's land mass. Deserts are classified by location and dominant weather pattern. Trade wind deserts are formed by the dissipation of cloud cover by the dry trade winds and include the Sahara. Midlatitude deserts, such as the Sonoran Desert, form between 30 and 50 degrees north and south latitude and are far inland of oceans. Rain shadow deserts form in the lees of high mountain ranges. Coastal deserts such as the Atacama are affected by cold ocean currents that flow parallel to the coast and generally form on western edges of continents. Monsoon deserts form as a result of monsoons losing water in heavy, seasonal rains as they move inland. Polar deserts such as the Dry Valleys of Antarctica receive little rainfall annually and have temperatures that do not exceed 10°C (Walker 1996). A world map of the Köppen-Geiger climate classification types, including arid and semi-arid regions (Group B) and Mediterranean climates (types Csa and Csb), is presented in Figure 1-1.

The three major hot U.S. deserts are the Chihuahuan Desert (Arizona and New Mexico), Sonoran Desert (southwestern Arizona and southeastern California), and Mojave Desert (southeastern California and portions of Nevada and Arizona). The Great Basin Desert (parts of Utah, Oregon, Idaho, Wyoming, Colorado, Nevada and Arizona) is the largest cold desert in the United States (Lee et al. 2011). The arid and semi-arid regions of the United States are shown in Figure 1-2. The different humidity zones—including hyper-arid, arid

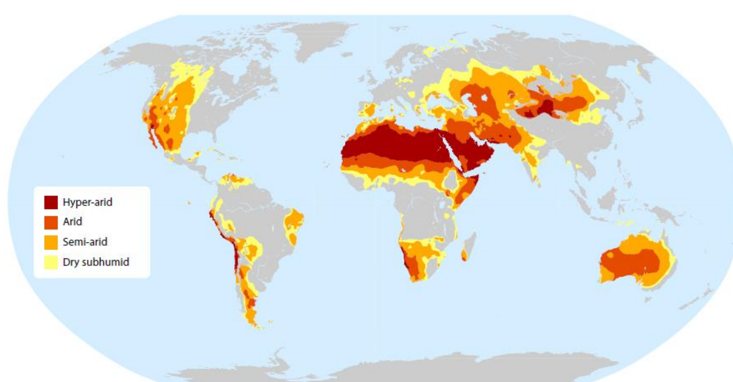

Figure 1-1. World map of hyper-arid, arid, semi-arid and dry subhumid regions.

Source: FAO (2015). Used by permission of FAO. Copyright 2016 FAO.

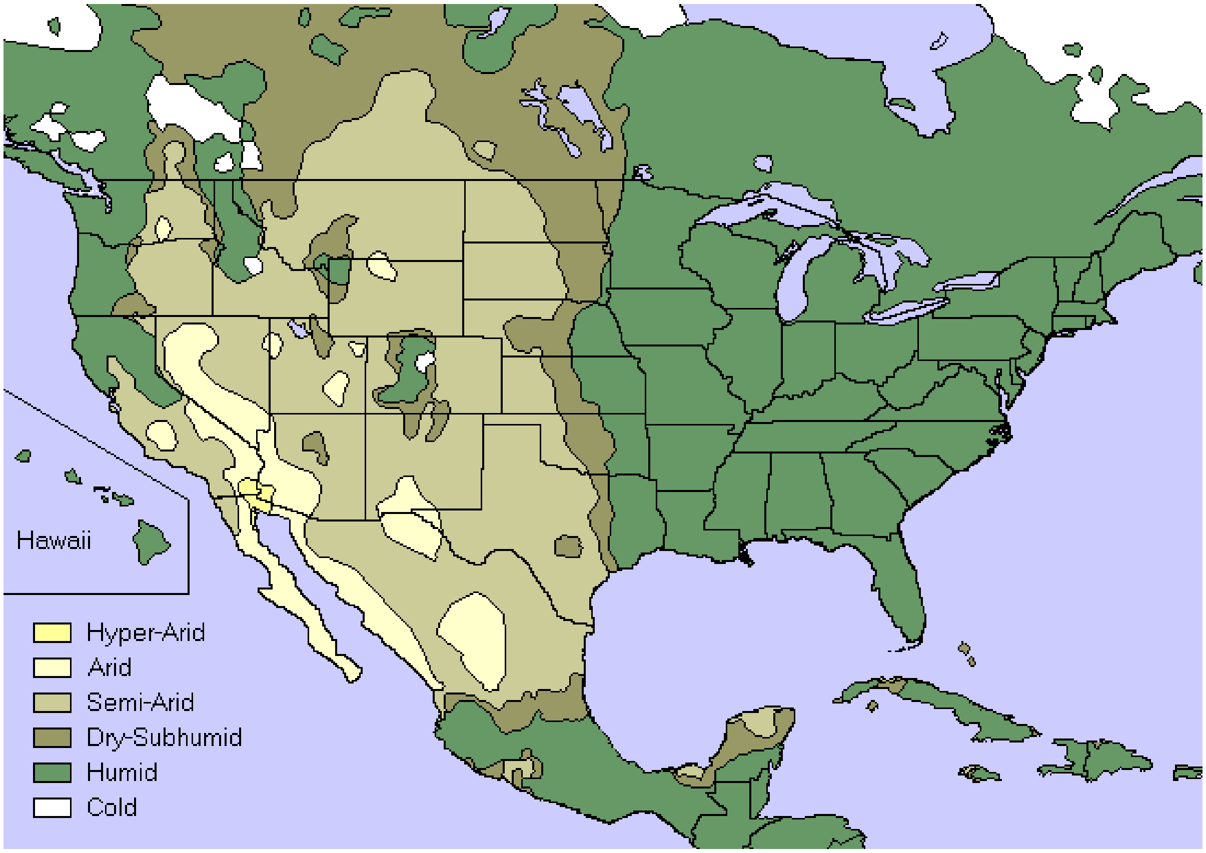

Figure 1-2. United States humidity zones.

Source: OALS (2002).

and semi-arid—follow the designations of the United Nations Environmental Programme, reflecting variations in the aridity index.

1.3. Green infrastructure for arid and semi-arid regions of the United States

Most green infrastructure practices were first developed in temperate climates, but most also are applicable to arid and semi-arid regions, although they may require modification. Green infrastructure can be a cost-effective approach to stormwater management and water conservation in arid and semi-arid regions, reducing runoff, conserving water, recharging ground water, conserving energy and improving air quality (USEPA 2010b). Design elements for green infrastructure that are applicable to arid and semi-arid regions of the United States are listed in Table 1-1. The primary application for each design element is indicated, either for managing stormwater close to its source or conserving stormwater to reduce potable water demand (or both). Design elements can be implemented at a range of scales, from the scale of local sites by individual property owners to larger scales that affect entire watersheds or portions of watersheds, and some design elements can be applied both at the site and multisite scales.

The design elements in this section are described first at the site-scale, and then watershed-scale practices are described. Within those site-scale practices, applications for stormwater management and conservation are presented. Site-scale design elements for related purposes of

Table 1-1. Green infrastructure in arid and semi-arid regions of the United States

Design Element	*Stormwater Application*		*Scale*	
	Management	*Conservation*	*Site*	*Watershed*
Bioswales	x		x	
Green roofs	x		x	
Permeable pavement	x		x	
Planter boxes	x		x	
Rain gardens/bioretention cells	x		x	
Integrated systems (e.g., green streets)	x		x	x
Land conservation	x			x
Riparian buffers	x			x
Urban tree canopies	x	x		x
Rain barrels or cisterns	x	x	x	
Agricultural water harvesting		x	x	x

Other design elements: Green walls (primary application: energy conservation), vegetative filter strips (primary application: pollution control).

energy conservation and pollution control also are included. Integrated systems comprise combinations of different practices that can be implemented at the site or larger scales.

1.3.1. Site-scale practices—stormwater management

1.3.1.1. Bioswales

Bioswales are vegetated, xeriscaped or mulched channels that capture stormwater runoff, slow its flow and enhance infiltration as the water flows downslope through the channels. Bioswales are used to treat and retain runoff. They are linear features and often are installed along streets and parking lots (USEPA 2015s). In arid and semi-arid regions, the vegetation selected should be appropriate to the climate, and climate-specific maintenance techniques are needed (USEPA 2010b).

1.3.1.2. Green roofs

Green roofs, also known as vegetative roofs, are flat or sloping roofs covered with growing media that support vegetation. The media and vegetation are designed to allow infiltration and storage of rainfall and evapotranspiration of stored water, as well as to treat stormwater. Green roofs also can provide recreational space in urban areas. Green roofs are designed as extensive or intensive systems. Extensive green roofs are shallow (6 inches or less) and tend to be designed for specific engineering or performance goals, whereas intensive green roofs can be much deeper and can include landscaping elements such as walkways, lawns, large perennial plants and trees (Miller 2016). In arid and semi-arid regions, green roofs require irrigation, but appropriate design approaches—including using a greater media depth, planting native and drought-adapted species and applying drip irrigation—can increase water efficiency. Green roofs also can be designed for irrigation by sources other than municipal water supplies (USEPA 2010b). Figure 1-3a shows a view of EPA Region 8's extensive green roof installed in Denver, Colorado. An example of an intensive green roof installed in a cool desert climate is shown in Figure 1-3b.

a) b)

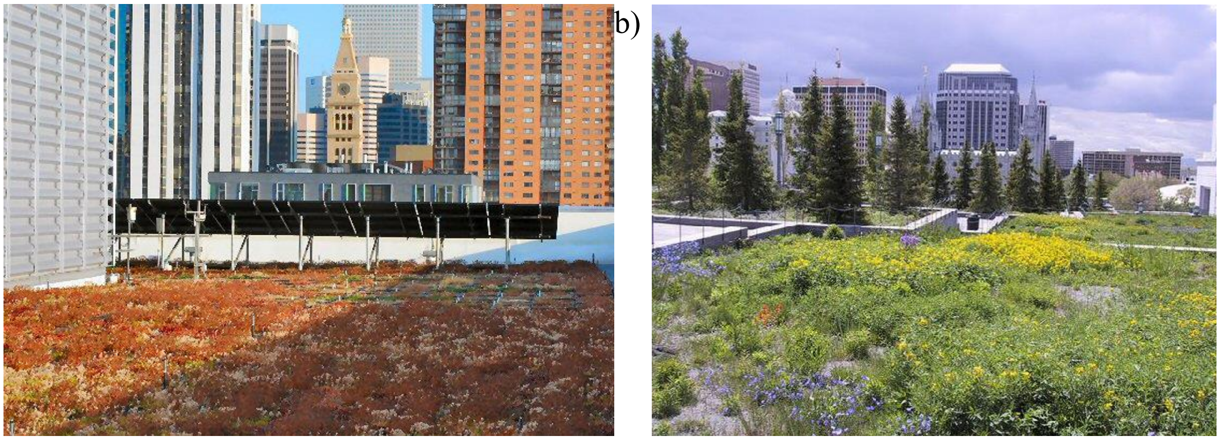

Figure 1-3. Green roofs installed in semi-arid regions of the United States.

Extensive green roof installed at the EPA regional office building in Denver, Colorado (a), and intensive green roof installed on the Church of Jesus Christ of the Latter-Day Saints Conference Center in Salt Lake City, Utah (b).

Source: USEPA Region 8 (2016).

1.3.1.3. Permeable pavement

Permeable pavement includes a range of technologies that allow stormwater to infiltrate and be stored where it falls. Permeable pavement can reduce stormwater runoff and improve water quality. Permeable pavement technologies include pervious concrete, porous asphalt and permeable interlocking pavers. Permeable pavement systems generally overlay several layers of bedding into which water drains and from which it infiltrates into the soil below. Permeable friction course is a type of permeable pavement where a layer of porous asphalt pavement is placed on top of a regular impermeable roadway (USEPA 2010b, 2015s).

1.3.1.4. Planter boxes

Planter boxes are rain gardens with vertical walls and open or closed bottoms. Like rain gardens, they collect runoff from surrounding impervious surfaces and allow it to soak into the soil. Planter boxes are used primarily in streetscaping in space-limited locations such as dense urban areas (USEPA 2015s).

1.3.1.5. Rain gardens and bioretention cells

A rain garden (see Figure 1-4) is a depressed area that collects precipitation that runs off from surrounding impervious surfaces (e.g., roof, driveway, parking lot, street) and allows it to soak into the ground, where it infiltrates into the soil and/or is evapotranspired back into the atmosphere. Rain gardens often are distinguished from more complex systems with enhanced drainage layers and amended soils, referred to as bioretention cells. In addition to stormwater management, rain gardens can play an important role in water conservation in arid or semi-arid regions because they rely on precipitation for their water needs. In these regions, the limitations of the water supply must be considered in design, particularly in selecting vegetation, as well as maintenance planning (USEPA 2010b, 2015s).

Figure 1-4. Rain garden at the New Belgium Brewery in Fort Collins, Colorado.

Source: USEPA Region 8 (2016).

1.3.2. Site-scale practices—stormwater conservation

1.3.2.1. Rain barrels, cisterns and storage tanks

Rain barrels, cisterns and storage tanks store rainwater from rooftops or other impervious areas for later use, thereby reducing stormwater runoff and reducing irrigation demand. Smaller rain barrels can reduce runoff and irrigation demand on a site scale (see Figure 1-5), whereas large cisterns or storage tanks can capture larger proportions of stormwater and address more irrigation demand. Sizing depends on roof area; rainfall patterns, which are specific to climate; available space; and costs, which increase with capacity (USEPA 2010b).

1.3.3. Site-scale practices—other purposes

1.3.3.1. Green walls

Green walls are sustainable construction practices that cover a building envelope with vegetation. The term "green façade" refers to green walls in which climbing or hanging plants are trained to cover a wall using special support structures. "Living walls" refer to more complex systems in which pre-vegetated panels, vertical modules or planted blankets are fixed vertically to a structural wall or frame. The main benefits of living walls are insulation and improved outdoor air quality (Feng and Hewage 2014).

1.3.3.2. Vegetated filter strips

A vegetated filter strip is a strip or area of vegetation intended to remove contaminants from overland flow. The purpose of installing vegetated filter strips is to remove suspended solids and reduce dissolved contaminant loadings in runoff. Vegetated filter strips are planted preferentially with permanent herbaceous plants (NRCS 2010).

Figure 1-5. Rainwater cistern installed at a residence in Tucson, Arizona.

Source: USEPA (2010b).

1.3.4. Integrated systems

Integrated systems are green infrastructure comprised of multiple design elements conceived of as a system. A green street is an example of an integrated system designed on a neighborhood or watershed scale to manage and treat stormwater. Green streets also can beautify streets and slow traffic. Examples of green streets (see Figure 1-6) are rain gardens installed in rights-of-way, medians, traffic circles and chicanes, with rainwater directed into the rain gardens and bioswales by adding curb cuts or installing curbs flush with the ground (USEPA 2010b). Construction of green streets can include features to increase their water storage capacity, such as dry wells and infiltration galleries.

Figure 1-6. Demonstration street median in Santa Fe, New Mexico.

Source: USEPA Region 6 (2014).

1.3.5. Watershed-scale practices—stormwater management and conservation

1.3.5.1. Land conservation

Land conservation through protecting open spaces and sensitive natural areas can improve water quality and reduce flooding. Land conservation approaches are particularly applicable to stormwater management in urban areas, where they also provide social benefits by increasing recreational opportunities. Sensitive natural areas in arid and semi-arid environments include riparian areas and steep hillsides (USEPA 2015s).

1.3.5.2. Riparian buffers

Riparian buffers restrict development in the land adjacent to washes, arroyos, creeks or streams. They are intended to reduce erosion and preserve the riparian channel. They can provide environmental and social benefits (e.g., recreational trails within riparian buffers). By providing a network of habitats, they also increase wildlife diversity (USEPA 2010b).

1.3.5.3. Urban tree canopies

Restoration of the urban tree canopy is a green infrastructure approach that cities can take to manage stormwater. Trees reduce and slow stormwater flow by intercepting precipitation in their leaves and branches (USEPA 2015s).

1.3.5.4. Agricultural water harvesting

Agricultural water harvesting is defined as the “collection of runoff for its productive use.” Agricultural water harvesting can be implemented at the site scale by individual farmers as well as at larger scales. The term includes within-field microcatchments (catchment length 1 to 30 m), external catchment systems (catchments 30 to 200 m in length), and floodwater farming (e.g., permeable rock dams, water-spreading bunds). Agricultural water harvesting offers a low-cost alternative to irrigation (Critchley and Siegert 1991). Major techniques of agricultural water harvesting most applicable to a range of situations and geographic areas are presented in Table 1-2.

Table 1-2. Agricultural water harvesting techniques

Technique	*Classification*	*Main Uses*	*Description*
Negarim microcatchments	Microcatchment	Trees and grass	Closed grid of diamond shapes or open-ended "V"s formed by small earth ridges, with infiltration pits
Contour bunds	Microcatchment	Trees and grass	Earth bunds on contour spaced at 5–10 m apart with furrow upslope and cross-ties
Semicircular bunds	Microcatchment	Rangeland and fodder (also trees)	Semi-circular shaped earth bunds with tips on contour. In a series with bunds in staggered formation
Contour ridges	Microcatchment	Crops	Small earth ridges on contour at 1.5–5 m apart with furrow upslope and cross-ties Uncultivated catchment between ridges
Trapezoidal bunds	External catchment	Crops	Trapezoidal-shaped earth bunds capturing runoff from external catchment and overflowing around wingtips
Contour stone bunds	External catchment	Crops	Small stone bunds constructed on the contour at spacing of 15–35 m apart slowing and filtering runoff
Permeable rock Dams	Floodwater farming	Crops	Long, low rock dams across valleys slowing and spreading floodwater as well as healing gullies
Water-spreading bunds	Floodwater farming	Crops and rangeland	Earth bunds set at a gradient, with a "dogleg" shape, spreading diverted floodwater

Source: Adapted from Critchley and Siegert (1991). Used by permission of FAO. Copyright 2016 FAO.

1.4. Green infrastructure in developing countries

Green infrastructure techniques can be used to address domestic, livestock, agricultural and environmental water needs in developing countries. Water harvesting and storage for domestic and agricultural use can increase food production and sustain human habitation in arid and semi-arid regions, mitigating effects of seasonal dry spells. De-desertification also is a green infrastructure approach that uses vegetation to conserve water and reduce erosion.

1.4.1. Drinking water security

One of the 17 United Nations Sustainable Development Goals for 2015 to 2030 is to "ensure the availability and sustainable management of water and sanitation for all" (United Nations 2015). Water harvesting technologies applicable to developing countries are those that are easy to construct, use local labor and do not require external funding. Technologies for container and in-soil storage of rainwater that can be used to address drinking water security in arid and semi-arid regions of developing countries include small storage in containers (e.g., rain jars, ferro-cement tanks, stone masonry tanks), larger storage in containers (e.g., open reservoirs, cisterns), small in-soil storage measures (e.g., contour trenches or ridges, terraces), and large in-soil storage measures (e.g., spate irrigation, subsurface dams, sand dams). To be sustainable, water harvesting projects must be applicable to local physical, cultural and economic circumstances (Lasage and Verburg 2015).

1.4.2. De-desertification

Desertification threatens large areas of arid and semi-arid lands worldwide. Desertification results from various factors, including climatic variations and human activities. The Food and Agriculture Organization (FAO) of the United Nations conducted a comprehensive analysis of afforestation, reforestation and restoration projects and initiatives in arid, semi-arid and dry subhumid climates (referred to as "drylands" by the FAO). Forests and trees are important in de-desertification efforts and provide such environmental services in drylands as food for humans and livestock, products for generating income, increased water infiltration, reduced soil erosion, moderation of local climates, increased soil fertility, habitat for flora and fauna, and cultural services. Restoration actions include habitat protection, assisted regeneration, sand dune stabilization and tree planting (see Figure 1-7). Sustainable de-desertification of drylands requires a landscape approach. Practitioners need to choose the most cost-effective restoration strategies, protect and manage restoration initiatives, promote natural regeneration, and plant when necessary. Monitoring and evaluation provide feedback on restoration activities. The FAO's report provides case studies of dryland restoration experiences (FAO 2015).

Figure 1-7. Dune stabilization in Mauritania.

Source: FAO (2015). Used by permission of FAO. Copyright 2016 FAO.

1.5. Benefits of green infrastructure in arid and semi-arid regions of the United States

Green infrastructure has the potential to provide stormwater management and conservation benefits, as well as social and economic benefits, in arid and semi-arid regions of the United States. Stormwater management benefits include reduced flooding, reduced erosion and improved surface water quality. Stormwater conservation benefits include increased ground water recharge and reduced water imports.

1.5.1. Stormwater management

Green infrastructure may represent a more cost-effective approach to stormwater management than traditional practices. Green infrastructure reduces flooding by increasing infiltration, evapotranspiration and water storage where precipitation falls. Increasing infiltration also recharges ground water reserves and can benefit aquatic habitats. Another environmental benefit of green infrastructure for stormwater management is that it improves water quality by reducing runoff and allowing runoff to be treated by soils and vegetation (USEPA 2010b). Reducing runoff can provide benefits for mitigating soil erosion, which causes upstream and downstream problems. Soil erosion from agricultural lands causes topsoil loss, resulting in increased susceptibility to drought. Downstream, sediment loads lead to operational costs for desilting such infrastructure as irrigation canals and hydroelectric power dams. Vegetative filter strips and reforestation are two green infrastructure approaches used to address this problem (Betrie et al. 2011).

1.5.2. Stormwater conservation

Green infrastructure also may be a cost-effective approach for conserving stormwater to address potable water needs. In cities and towns in arid and semi-arid regions of the United States, impervious surfaces and engineered conveyance systems reduce infiltration of precipitation into the ground water. Green infrastructure practices that increase infiltration can recharge ground water resources, a potential source of potable water. Some green infrastructure practices that conserve stormwater for reuse also can remove pollutants from stormwater, improving water quality, making it suitable for reuse to reduce demands on potable water. Green infrastructure has the potential to reduce landscape irrigation. Where water is imported to meet local demands, as is done in many cities and towns in arid and semi-arid parts of the United States, rainwater harvesting for nonpotable uses such as landscape irrigation reduces demand on the potable water supply and the need for costly water imports (USEPA 2010b). Water rights laws can affect the legality of water harvesting, however, as described in Section 1.6.2.

1.5.3. Social benefits of green infrastructure

Green infrastructure has many social benefits. It can improve public health by reducing the urban heat island effect, improving air quality, providing recreational opportunities and mitigating carbon dioxide emissions. Green infrastructure also beautifies neighborhoods, calms traffic and builds communities, improving the urban environment.

1.5.3.1. Improve public health

Extreme heat, poor air quality and lack of access to pedestrian-friendly landscapes are public health concerns that are linked to issues of environmental justice. Socially disadvantaged neighborhoods often experience greater negative health impacts from extreme heat. Populations such as the elderly, people with physical or mental illnesses, the very young, individuals living alone, and people with low socio-economic status are more vulnerable to extreme heat.

Removing pavement and planting vegetation can reduce the urban heat island effect by cooling and shading urban neighborhoods (USEPA 2010b). Four types of green infrastructure typically are used for cooling in urban areas: green open spaces, shade trees, green roofs, and green walls and façades (Norton et al. 2015). In a modeling study using data from Phoenix, Arizona, xerophytic shade trees were predicted to reduce urban heat island effects, particularly at the site scale (i.e., the residential lot and adjacent buildings) and at night. Compared to mesic landscaping, however, xeriscaping appeared to increase temperatures at all spatial scales and temporal periods (Chow and Brazel 2012). Installation of permeable pavement also might be expected to influence urban temperatures because of the insulating properties of its high air void content and high albedo relative to black asphalt. Modeling studies have indicated that porous asphalt pavement would have higher daytime surface temperatures but lower nighttime temperatures compared to materials with similar albedos (i.e., traditional dense-graded asphalt and Portland cement concrete pavement), indicating that assessing the effect of different types of pavement on the urban heat island effect is complex (Stempihar et al. 2012). Permeable pavement under wet conditions cooled surface temperatures by 15 to 35°C compared with impermeable pavement under summer conditions in semi-arid Davis, California (Li et al. 2013).

Green infrastructure also has the potential to improve public health by mitigating global climate change and improving air quality. Soils and plant biomass sequester carbon, reducing atmospheric carbon dioxide concentrations. For example, green roofs installed in semi-arid regions have been shown to sequester carbon (Ondoño, Martinez-Sanchez and Moreno 2016b). Poor air quality is a particular problem for children and the elderly. Vegetation removes air pollutants and can mitigate the formation of smog, which is a particular health problem in urban areas (USEPA 2010b).

Many green infrastructure projects incorporate pedestrian- and bicycle-friendly designs. For example, intensive green roofs can provide recreational space, which can be particularly valuable in dense urban settings (Jiang, Yuan and Piza 2015). The green street design in Los Angeles shown in Figure 1-8 incorporated new sidewalks. Pedestrian- and bicycle-friendly recreational spaces can promote public health by fostering physical activity (USEPA 2010b).

Figure 1-8. Sidewalk and bioswale in the completed public right of way after the Elmer Avenue Neighborhood Retrofit in Los Angeles, California.

Source: Council for Watershed Health (2015a). Photo credit: Council for Watershed Health.

1.5.3.2. Beautify neighborhoods

Green infrastructure provides a sustainable approach to irrigating private gardens and public green spaces. Landscapes maintained by passive and active rainwater harvesting beautify neighborhoods and urban areas (USEPA 2010b).

1.5.3.3. Calm traffic

Many green infrastructure design elements implemented in streets and alleys reduce street widths and introduce curves. The green infrastructure techniques can slow traffic (USEPA 2010b).

1.5.3.4. Build communities

Beautifying neighborhoods and creating a unique sense of place with green infrastructure can increase interactions among neighbors. Many green infrastructure projects involve neighbors working together to beautify their communities and make them more livable (USEPA 2010b).

1.5.4. Economic benefits of green infrastructure

The economic benefits of green infrastructure include reduced landscape and building maintenance costs, increased ground water resources, reduced water imports, lower energy costs and reduced stormwater management costs.

1.5.4.1. Reduce landscape and building maintenance costs

Landscapes planted with drought-adapted plants and irrigated by rainwater harvesting cost less to maintain (USEPA 2010b). Buildings that include elements of green infrastructure can have lower maintenance costs as well. Green roofs can extend the lifetime of roofs, requiring replacement only every 40 to 50 years, compared with 10 to 20 years for conventional roofs (Jiang, Yuan and Piza 2015). A lifecycle costs-versus-benefits comparative analysis between a green roof, black roof and reflective roof in Utah showed that the green roof alternative was a better investment despite larger initial capital costs (Wu and Smith 2011).

1.5.4.2. Increase ground water resources and reduce water imports

Using ground water resources for public water supplies is costly. Costs associated with pumping ground water and importing ground water can be reduced by green infrastructure practices that conserve water and increase ground water recharge. Rainwater harvesting decreases landscape irrigation demands on the public water supply (USEPA 2010b).

1.5.4.3. Lower energy use

Green infrastructure can reduce energy used to import, treat and distribute municipal water, as well as reduce energy use by buildings for heating and cooling. The transportation and treatment of water can represent a significant fraction of electricity consumed by municipalities in arid and semi-arid regions of the United States (USEPA 2010b).

By providing insulation and shade and dissipating heat through evapotranspiration, green roofs have the potential to reduce energy use for building cooling. Thermal and energy simulations have shown that green roofs potentially reduce cooling energy consumption significantly in Santiago, Chile, which has a Mediterranean climate (Vera et al. 2015). Modeling of electricity and heating energy costs and consumption in the semi-arid United States, however, has shown that savings in cooling costs as compared with white roofs may derive primarily from reduced peak demand rather than reduced overall consumption (Sailor, Elley and Gibson 2012). The summer and winter energy savings from green roofs in hot and dry climates with mild winters (e.g., Los Angeles, California—a Mediterranean climate) can be enhanced by installing a variable insulating system, an insulated smart plenum coupled or decoupled to the indoor temperature (La Roche and Berardi 2014).

The shading, insulating and heat dissipating properties of green walls have the potential of reducing energy use for heating and cooling. A modeling study of three types of living walls in a Mediterranean climate (Los Angeles) showed substantial energy savings in cooling but little effect on energy use for heating. The cooling effects are mainly from shade and evapotranspiration (Feng and Hewage 2014). A green façade lowered temperatures by 5°C compared to a bare wall during the peak summer month of July for a building in the United Arab Emirates (Haggag, Hassan and Elmasry 2014). In a modeling study of the effects of green walls in a semi-arid climate in China, indoor air temperatures were lowered by as much as 15°C compared with ordinary construction (Di, Lin and Wang 2014).

1.5.4.4. Reduce stormwater management costs

Green infrastructure also can reduce the costs of building stormwater management infrastructure. For example, green roofs can reduce or eliminate the need for stormwater detention vaults or ponds, reducing stormwater management costs (Jiang, Yuan and Piza 2015).

1.6. Unique considerations of arid green infrastructure

Arid and semi-arid climates are defined by their precipitation and temperature. Geographically, they occur at a wide range of latitudes and from a range of interactions between weather and geography. Water stress in arid and semi-arid regions of the United States, however, is caused by other factors in addition to climate (e.g., growing population). Another unique aspect of implementing green infrastructure in arid and semi-arid regions of the United States is the need to navigate federal and local legislation. Finally, the characteristics of precipitation and runoff unique to desert and semi-arid regions in the United States complicate the management of stormwater and conservation of precipitation.

1.6.1. Causes of water stress in arid and semi-arid regions

Water stress in the arid and semi-arid regions of the United States is caused by a range of factors. These include droughts, growing population, ground water depletion, irrigation and climate change. Natural variation in precipitation—as well as effects on precipitation patterns from anthropogenic climate change—can lead to drought. Green infrastructure, which increases infiltration of stormwater and ground water recharge, can play a role in adaptation to drought. Increasing human population in the arid and semi-arid regions of the United States, particularly in urban areas, places increasing stress on water resources. The total population of the West is growing at a faster rate than the total U.S. population. Population growth is greatest in incorporated areas, which also are growing faster in the West than in the United States as a whole. As a result, 76.4 percent of the population of the West now lives in incorporated places (Cohen, Hatchard and Wilson 2015).

In the arid and semi-arid West and Southwest, ground water is a significant source of water for domestic and agricultural use. Changes in freshwater reserves are being monitored by new satellite technologies. Data from California's Central Valley show the depletion in ground water during the period from 2003 to 2009 (AMNH 2015).

Irrigation for residential landscapes and agriculture adds to water stress in arid and semi-arid regions. Approximately one-third of all freshwater withdrawals in the United States are used for irrigation (USEPA 2016j).

Climate change is predicted to have a significant effect on water supplies throughout the United States. An analysis performed for the Natural Resources Defense Council (2010) found that by 2050, more than one-third of all U.S. counties will be at risk for water shortages because of global warming. The arid and semi-arid regions of the Southwest and West are at particular risk from water shortages because of climate change.

1.6.2. Stormwater management laws and the navigation of water rights

EPA policy encourages the integration of green infrastructure into National Pollutant Discharge Elimination System (NPDES) permits and combined sewer overflow (CSO) remedies. Municipal Separate Storm Sewer System (MS4) operators, who are required to obtain an NPDES permit and develop a stormwater management program, are increasingly integrating green infrastructure into their MS4 permits. EPA supports the use of green infrastructure for long-term control and remediation of noncompliant CSOs (USEPA 2016f). Green infrastructure practices also can be incorporated into total maximum daily load (TMDL) reports to plan for impaired waters meeting water quality standards (USEPA 2008a).

Local mandates for meeting a portion of landscaping requirements with harvested rainwater, requirements for water conservation or rainwater harvesting in new construction, and requirements for controlling runoff using green infrastructure practices also have been implemented in arid and semi-arid regions of the United States (USEPA 2010b).

Water rights laws comprise a complex legal landscape in the arid and semi-arid West. The prior appropriation system, which grants individuals the right to put water to beneficial use based on the priority of the user (i.e., "first in time, first in right"), applies in much of the West. State water laws can affect green infrastructure practices (USEPA 2010b). In some states, precipitation belongs to existing water-rights owners. In others, rainwater harvesting is restricted based on water quality and public health concerns. Rainwater harvesting has been viewed legally in some states (e.g., Colorado) as a potential injury to senior water rights and has been prohibited. Colorado currently is the only state to ban the use of rain barrels. Among states with arid and semi-arid regions, pending legislation in California will require the State Water Resources Control Board to address the potential for storm-induced overflow from an impoundment storing recycled water (NCSL 2016).

1.6.3. Financial incentives for stormwater conservation

At the same time, many states and municipalities are promoting rainwater harvesting through financial incentives. State tax credits, rebates for installing rainwater harvesting systems, and reductions in stormwater management fees in return for using rainwater harvesting systems are approaches that have been used in the West and Southwest (USEPA 2010b).

1.6.4. Characteristics of precipitation and runoff in the arid and semi-arid regions of the United States

Runoff from soils in arid and semi-arid regions is affected by vegetation, the surface properties of nonvegetated soils, and creation of impervious surfaces through development. Intact nonvegetated soils usually are covered by biological soil crusts, communities of cyanobacteria, lichens and mosses, which reduce runoff on a local scale. When the crusts are disrupted by anthropogenic activity, such as hoof action by livestock, the transport of nutrients by water, soil and organic matter within the desert ecosystem is altered (Belnap et al. 2005). Intact biological soil crusts resist sediment transport (Rodríguez-Caballero et al. 2014). Soil type also can affect infiltration, with less infiltrative soils requiring design modifications for green infrastructure implementation. In urban arid and semi-arid areas, such impervious surfaces as parking lots, roads and rooftops decrease the amount of precipitation absorbed by soil, increasing runoff (USEPA 2010b).

The problem for stormwater management in arid and semi-arid regions posed by disturbed soils and impervious surfaces is exacerbated by precipitation patterns. Rainfall in deserts can be of short duration but high in intensity (Walker 1996). The precipitation patterns of the arid and semi-arid regions of the United States vary. In the Great Basin desert, precipitation is relatively uniform throughout the year compared to the other North American deserts. The Mojave Desert has a winter rainy season. In the Chihuahuan Desert, rainfall is predominantly in the summer (June to September) with occasional winter rains. The Sonoran Desert experiences extremely rare precipitation at low elevations but more precipitation at higher elevations (Lee et al. 2011).

In addition to increased runoff, human activity can impair the quality of stormwater. During dry periods, oils, pesticides and other organic pollutants; sediments; animal waste; and trash can accumulate. When precipitation occurs, runoff flows across the land, carrying a pulse of wastes and pollutants into receiving waters, which is a particularly acute problem when precipitation events are rare, as in hot desert climates (USEPA 2010b).

Chapter 2.
Arid Green Infrastructure Resources at EPA

EPA provided resources at the program and regional levels to policymakers and practitioners to support the application of green infrastructure for stormwater management and conservation. This chapter focuses on EPA's support for green infrastructure implementation in arid and semi-arid regions of the United States. Technical assistance projects, modeling and decision support tools, operations and maintenance guidance, design and implementation guidance, and funding opportunities developed by EPA program offices are described, including resources that focus on arid and semi-arid regions, where applicable. This chapter also surveys resources offered by EPA program offices that provide information about green infrastructure performance, contributions to climate resiliency, current intramural and extramural research efforts, benefits, cost-benefit analyses, policy guides and tools, and integration into federal regulatory programs. An overview is provided of EPA collaborations supporting green infrastructure. Finally, projects and resources implemented and developed by EPA regional offices in regions that include areas with arid and semi-arid climates are described in this chapter.

2.1. Green infrastructure program

EPA provides strong support for and promotes the benefits of using green infrastructure for cities and wastewater treatment plants in protecting drinking water supplies and public health, mitigating overflows from combined and separate sewers, and reducing stormwater pollution (USEPA 2007). EPA has collaborated with other agencies and organizations to develop the *Managing Wet Weather With Green Infrastructure: Action Strategy* (USEPA 2008b). A Web-based green infrastructure resource center to assist communities with building, designing and implementing green infrastructure practices that are in compliance with regulatory guidelines also has been established at EPA (USEPA 2016b). Resources available on this website include educational materials; modeling tools; design, implementation, and operations and maintenance guidelines; and information about collaborations between EPA and its partners to advance the implementation of green infrastructure practices. EPA's Green Infrastructure Wizard (GIWiz) is a Web application that provides access to EPA green infrastructure tools and resources (USEPA 2015n). Also posted on the website is *Tools, Strategies and Lessons Learned From EPA Green Infrastructure Technical Assistance Projects*, which summarizes green infrastructure solutions for stormwater management challenges of municipalities (USEPA 2015r). Technical assistance products produced by communities located in arid and semi-arid regions and for which EPA provided technical assistance to address barriers to using green infrastructure and share lessons learned are presented in Table 2-1.

2.1.1. Plan and maintain green infrastructure

Building sufficient green infrastructure requires planning, and EPA has several resources for implementing green infrastructure in the community, including modeling tools that support planning and design decisions, guidance for operations and maintenance, details on design and implementation, and information on available funding sources.

Table 2-1. EPA technical assistance projects in arid and semi-arid regions

Project Type	*EPA Region*	*Project Name*	*City*	*State*
Conceptual design	6	Imperial Building Site Design	Albuquerque	NM
Conceptual design	6	Pueblo de Cochiti Green Infrastructure Concept Design	Pueblo de Cochiti	NM
Conceptual design	8	Conceptual Green Infrastructure Design for the Blake Street Transit-Oriented Development Site, City of Denver (EPA-830-R-13-002)	Denver	CO
Conceptual design	9	Building Resilience to Drought in Ozone Park (EPA-832-R-15-010)	Santa Monica	CA
Conceptual design	10	Fairview Avenue Green Street Conceptual Design (EPA-832-R-15-011)	Boise	ID
Guidance development	8	Green Infrastructure Checklists and Renderings	Denver	CO
Guidance development	9	Tools to Promote Green Infrastructure Implementation in Arid and Semi-Arid Regions	Pima County	AZ
Policy review/ recommendations	9	Green Infrastructure Barriers and Opportunities in Phoenix, Arizona (EPA-830-R-13-005)	Phoenix	AZ
Policy review/ recommendations	9	Green Infrastructure Barriers and Opportunities in the Greater Los Angeles Region (EPA-833-R-13-001)	Los Angeles	CA

Source: Adapted from USEPA (2015r).

2.1.1.1. Modeling and decision support tools

The modeling tools provided by EPA allow users to predict environmental outcomes of different green infrastructure design and management approaches. The models range from site to watershed scale. Outputs include runoff volume, runoff rate, pollutant loading and cost. Models range from simple sizing and cost spreadsheets that produce quick estimates of cost and performance to simple models for use as screening- and planning-level tools (e.g., EPA National Stormwater Calculator) to complex models (e.g., EPA Stormwater Management Model [SWMM] with Low-Impact Development [LID] Controls). These models require such inputs as soil conditions, vegetation characteristics, topography, impervious cover, precipitation, evaporation, land use, land cover and water costs, allowing them to be applied to specific locations in the arid and semi-arid West and Southwest (USEPA 2015j).

Regarding cost-effectiveness, EPA's Watershed Management Optimization Support Tool (WMOST) is a tool for local water resources managers and planners to screen potential water resources management options, including green infrastructure, across their watershed or jurisdiction for cost-effectiveness as well as environmental and economic sustainability (Detenbeck et al. 2016).

For land use change, EPA's Automated Geospatial Watershed Assessment (AGWA) tool is designed to help manage and analyze watershed water quantity and quality. AGWA provides qualitative estimates of runoff and erosion relative to landscape change (USEPA 2016a). AGWA was tested for its ability to simulate stormwater runoff responses in semi-arid landscapes (Korgaonkar et al. 2014).

2.1.1.2. Operations and maintenance

Recognizing that green infrastructure requires regular inspections and maintenance for effective operation, EPA also provides resources about what to look for when inspecting green infrastructure and how frequently to conduct maintenance activities. These resources provide general guidance rather than being targeted for arid and semi-arid conditions (USEPA 2015l).

2.1.1.3. Design and implementation

EPA has compiled resources for design and implementation of green infrastructure, including design manuals, information about addressing common design challenges, implementation information and homeowner resources. One of the design manuals, *Green Infrastructure for Southwestern Neighborhoods* (MacAdam 2012), is directly applicable to the arid and semi-arid United States. Some of the design challenges also are applicable to the West and Southwest. Information is provided about addressing problems with poor-quality urban soils (applicable to cities in arid and semi-arid regions) and limited water resources for irrigation. For limited water resources, possible solutions include planning a water budget, integrating low-water-use plants, using efficient irrigation systems, considering soil amendments, using mulches, and maintaining the xeriscape. For implementation, references on lessons learned from construction mistakes and ensuring practices are built as designed are provided. In addition, EPA cites examples of guides for homeowners that have been produced by state and local governments, although none of the examples are specific to arid or semi-arid regions (USEPA 2016c).

2.1.1.4. Funding opportunities

Federal funding sources and tools to understand available funding opportunities from local, government and nonprofit organizations are provided by EPA. Federal agencies with grant and assistance programs include the U.S. Departments of Agriculture, Energy, Housing and Urban Development, Interior, and Transportation; the National Oceanic and Atmospheric Administration; the U.S. Economic Development Administration; and EPA (USEPA 2015i). General funding tools with recent information that may be relevant to arid and semi-arid regions of the United States include *Getting to Green: Paying for Green Infrastructure*, *Finance Options and Resources for Local Decision-Makers* (USEPA 2014) and a guide on community-based public-private partnerships for green infrastructure (USEPA Region 3 2015). In addition, the Water Infrastructure Finance and Innovation Act (WIFIA) program provides low interest rate financing for the construction of water and wastewater infrastructure under the Water Resources Reform and Development Act (WRRDA) of 2014.[1]

2.1.2. Learn about green infrastructure

In addition to construction resources, EPA's green infrastructure website provides information for learning more about implementation. These resources include information about what green infrastructure is and overcoming barriers to green infrastructure, performance of green infrastructure practices, the role of green infrastructure in climate resiliency, research on green infrastructure, the benefits of green infrastructure, cost-benefit resources, policy guides,

[1] Water Resources Reform and Development Act of 2014, Pub. L. No. 113-121, 128 Stat. 1193 (2014).

integrating green infrastructure into federal regulatory programs, and a green infrastructure webcast series.

2.1.2.1. Basics

EPA provides information about the types of green infrastructure elements that can be used by communities. Green infrastructure elements include downspout disconnection, rainwater harvesting, rain gardens, planter boxes, bioswales, permeable pavements, green streets and alleys, green parking, green roofs, urban tree canopies, and land conservation (USEPA 2015s). Examples of communities in arid and semi-arid regions implementing these elements include the Los Angeles Downspout Disconnection Program (City of Los Angeles 2009) and Elmer Avenue, a green street project in Los Angeles (Green 2010).

EPA also provides information on overcoming the barriers that municipalities and developers might face when determining whether green infrastructure is appropriate in a particular context. For municipalities, some of the barriers are perceptions that performance is unknown, costs of green infrastructure are high, the regulatory community is resistant to green infrastructure, green infrastructure conflicts with principles of smart growth, and green infrastructure conflicts with water rights laws; unfamiliarity with maintenance requirements and costs; conflicting codes and ordinances; and lack of staff and resources. EPA offers general strategies and resources to address these barriers. Regarding costs, EPA has compiled resources on cost-benefit analyses for green infrastructure (USEPA 2015e).

Developers may face skepticism about long-term performance and a perception of higher costs. Some of the same strategies suggested for municipalities to address perceptions that performance is unknown and costs are high apply to developers.

2.1.2.2. Performance

With respect to performance, EPA provides resources on databases and summary reports on green infrastructure practices in general, as well as resources on the performance of particular green infrastructure design elements (green roofs, permeable pavements, rainwater harvesting, rain gardens and planter boxes, bioswales, urban tree canopies and constructed wetlands) and watershed-scale studies of green infrastructure performance. Current databases include the International Stormwater Best Management Practices (BMP) Database, which provides BMP performance summaries (WERF 2016). EPA also summarized research on the performance of several green infrastructure practices in a report titled *Green Infrastructure for Stormwater Control: Gauging Its Effectiveness With Community Partners,* which includes data on costs and performance conducted in Denver and Phoenix (USEPA 2015h).

2.1.2.3. Climate resiliency

EPA provides information on using green infrastructure to improve climate resiliency. Green infrastructure practices can help communities manage flooding, prepare for drought, reduce the urban heat island effect, lower building energy demands, spend less energy managing water, and protect coastal areas. All of these effects of climate change will be relevant to arid and semi-arid parts of the United States (USEPA 2015g).

2.1.2.4. Research

EPA provides resources on research on green infrastructure conducted by the scientific, regulatory and development communities. Topics include performance, urban stormwater impacts, surface water impacts, ground water impacts, air quality impacts, green infrastructure and climate, green infrastructure and wildlife conservation, and the economics of green infrastructure (USEPA 2015p).

EPA scientists and engineers conduct research on topics including assessments of green infrastructure impacts on watersheds; best practices for design, operation and maintenance of green infrastructure; decision-support guidance for sustainable communities; and technical assistance with green infrastructure (USEPA 2015m).

EPA's Office of Research and Development (ORD) supports research on green infrastructure. ORD's Safe and Sustainable Water Resources (SSWR) research program includes in its strategic plan (2016–2019) a project focusing on green infrastructure models and tools and a project on green infrastructure information and guidance based on community partnerships (USEPA 2015q). Through its Science To Achieve Results (STAR) grant program, ORD also is supporting research on a decision-support tool for life-cycle cost assessment and optimization of green, grey and hybrid stormwater infrastructure (USEPA 2016e) and the creation of a National Center for Sustainable Water Infrastructure Modeling Research, which will facilitate sharing of green infrastructure tools and research advancements with local communities and stakeholders (USEPA 2016g).

2.1.2.5. Benefits

Green infrastructure benefits are described by EPA (USEPA 2015b). These include benefits for water quality and quantity, air quality, climate resiliency, habitat and wildlife, and communities. General resources on these topics may apply to arid and semi-arid regions. An example of a project on water supply and green infrastructure in the semi-arid West is the Colorado Climate Preparedness Project (Western Water Assessment 2011).

2.1.2.6. Cost-benefit resources

Cost-benefit resources for green infrastructure compiled by EPA include resources on cost analysis, cost-benefit analysis and tools. Resources include case studies and literature reviews. General tools that estimate the economic benefits of green infrastructure also are provided (USEPA 2015e). One case study includes locations in the arid and semi-arid United States (Cheyenne, Wyoming; Fort Collins, Colorado; and Glendale, Arizona) (McPherson et al. 2005).

2.1.2.7. Policy

Policy guides and tools are available to help municipalities in implementing green infrastructure. EPA has produced an online municipal handbook that describes funding options, retrofit policies, green street programs and policies, rainwater harvesting policies, and incentive mechanisms (USEPA 2015k). Other policy guides include guides on sustainability and case studies of policies adopted by municipalities to promote green infrastructure use, including those of San Jose, Santa Monica and Emeryville in California; Olympia in Washington; and Wilsonville in Oregon (USEPA 2010a). Additional policy tools cited are EPA's Water Quality Scorecard and a toolbox created by the Water Environment Research Foundation on effectively communicating and implementing green infrastructure concepts (USEPA 2015o).

2.1.2.8. Regulations

EPA provides information related to integrating green infrastructure into federal regulatory programs. These programs include MS4s, CSOs and TMDLs. EPA supports incorporating green infrastructure approaches into NPDES permits and CSO remedies and has produced fact sheets on green infrastructure permitting and enforcement. California is an example of a state that has integrated green infrastructure into its MS4 permits (USEPA 2016f). For CSO control plans and remedies, EPA has compiled documents to quantify green infrastructure contributions to CSO control plans (USEPA 2015c); created an index of EPA enforcement actions incorporating green infrastructure; and developed a template, Long-Term Control Plan-EZ (commonly known as LTCP-EZ), for small municipalities to use to assess the potential for green infrastructure controls to eliminate or reduce CSOs. Regarding TMDLs, EPA has developed a fact sheet on incorporating green infrastructure concepts into TMDLs and provides information on a case study in EPA Region 1 in which green infrastructure was used to retain and treat stormwater to reduce phosphorus loads (USEPA 2016f).

2.1.2.9. Webcasts

EPA is producing a series of webcasts aimed at public officials and practitioners who want to begin implementing green infrastructure or enhance existing green infrastructure programs (USEPA 2016d). The library of past webcasts includes *Green Infrastructure for Arid Communities*, which discusses green infrastructure implementation strategies in southern California and Tucson, Arizona (USEPA 2015f). EPA also has produced webcasts on green infrastructure as part of its Watershed Academy series (USEPA 2016d).

2.1.3. Collaborate with green infrastructure partners

EPA partners with organizations and communities to foster adoption of green infrastructure. Collaborations include issuing the Campus RainWorks Challenge to undergraduate and graduate students, participating in the Green Infrastructure Collaborative, recognizing community partners in each of EPA's regions, providing technical assistance to communities, and engaging citizens and municipalities through the Soak Up the Rain program.

2.1.3.1. Campus RainWorks Challenge

EPA's Office of Water sponsors an annual competition for undergraduate and graduate students to design innovative green infrastructure projects for their campuses. Students compete in two categories: Master Plan and Demonstration Project. A past winner from a semi-arid region is the University of Arizona (Second Prize, 2012). The American Society of Landscape Architects, American Society of Civil Engineers and Water Environment Federation assisted in the judging and outreach for the 2015 Challenge (USEPA 2015a).

2.1.3.2. Green Infrastructure Collaborative

The Green Infrastructure Collaborative is a network-based learning alliance formed in 2014 to help communities implement green infrastructure. Federal members include EPA and the U.S. Departments of Agriculture, Defense, Energy, Housing and Urban Development, Interior, and Transportation. Nonfederal members include more than 20 academic, nongovernmental and private sector organizations. EPA has compiled resources and tools produced by member organizations to advance green infrastructure implementation, including the Natural Resources Defense Council's issue paper on how implementing green infrastructure in California cities can address emerging water resource and climate challenges (NRDC 2009; USEPA 2015d).

2.1.3.3. EPA is supporting green infrastructure

In support of green infrastructure, EPA has produced policy memoranda encouraging the use of green infrastructure to meet regulatory requirements. EPA's *Green Infrastructure Strategic Agenda 2013* describes the actions that the Agency intends to take to promote green infrastructure implementation, focusing on federal coordination, Clean Water Act (CWA) regulatory support, research and information exchange, funding and financing, and capacity building (USEPA 2013). EPA also supports a voluntary integrated planning approach by municipalities to propose to meet multiple CWA requirements by identifying efficiencies from separate wastewater and stormwater programs and prioritizing projects to address the most serious water quality issues first. Implementing green infrastructure can lead to more sustainable and comprehensive solutions to these issues, and EPA has developed a framework to provide guidance on implementing an integrated planning approach (USEPA 2012). The Agency also has recognized community partners in each of EPA's regions for their commitment to green infrastructure, including Denver (Region 8), Los Angeles (Region 9) and Puyallup, Washington (Region 10).

In addition, EPA provides technical assistance to communities to advance the adoption of green infrastructure locally and develop knowledge and tools for a national audience. The program focuses on overcoming technical, regulatory and institutional barriers to green infrastructure and sharing lessons learned. Western and Southwestern jurisdictions that received technical assistance include Ada County, Idaho; Albuquerque, New Mexico; Denver; Pueblo de Cochiti, New Mexico; Santa Monica; Phoenix and Los Angeles (see Table 2-1). The results of the program are summarized in *Tools, Strategies and Lessons Learned From EPA Green Infrastructure Technical Assistance Projects* (USEPA 2015r, 2016k).

2.1.3.4. Soak Up the Rain program

EPA's Soak Up the Rain program offers citizens and municipalities access to information on green infrastructure practices, communication tools, and resources on green infrastructure benefits and funding as well as opportunities to share their stories with others (USEPA 2016h).

2.2. Regional programs

EPA Regions 6, 8 and 9 have developed their own materials on green infrastructure relevant to their respective locales. Resources include demonstration projects, region-specific guidance, funding opportunities and training events.

2.2.1. Region 6

EPA Region 6 has published information on its website on the basics of green infrastructure, green infrastructure projects within the region, funding opportunities for green infrastructure projects, and training events (USEPA Region 6 2016a). Projects in New Mexico are described in

Table 2-2. Other projects in Texas and Oklahoma are not located in the semi-arid parts of the states (USEPA Region 6 2016c). Funding opportunities, including local loans and grants, are provided on the EPA Region 6 website (USEPA Region 6 2016b). Training events also are listed on Region 6's website (USEPA Region 6 2016d).

Table 2-2. EPA Region 6 green infrastructure demonstration projects in the desert Southwest

Project	***Description***	***City***	***State***
Las Cruces Dam Restoration Project	Constructed wetlands	Las Cruces	NM
Stormwater Demonstration Median	Rain harvesting	Santa Fe	NM
Railyard Park and Plaza	Rain storage and harvesting	Santa Fe	NM

Source: USEPA Region 6 (2016c).

2.2.2. Region 8

The unique environment of the semi-arid West requires attention for implementing green infrastructure practices. The climate is dry with intermittent and unpredictable rainfall, and temperature differences between summer and winter are large with rapid freeze/thaw cycles. These conditions require the use of native plants that are drought tolerant and low maintenance (USEPA Region 8 2016).

2.2.2.1. Demonstration projects

Green infrastructure projects implemented in EPA Region 8 include green roofs, rain gardens, bioswales, bioretention ponds, porous pavement and rainwater harvesting (see Table 2-3). When implementing these practices, conditions specific to the region must be addressed and region-specific benefits may be realized.

Green roofs provide unique benefits in this region. The insulating properties of green roofs reduce energy expenses during the region's very warm summers and very cold winters. Because of high elevations, buildings in Region 8 are exposed to intense solar radiation, which damages the roof membrane. Vegetation helps protect the membrane from sun damage.

Flash floods from large storms are of concern in this region. Permeable pavement helps absorb stormwater runoff. Many types of porous pavements are more durable than traditional nonporous concrete in the face of the routine freezing and thawing cycles characteristic of Region 8 winters.

Regarding rainwater harvesting, water laws differ among the Region 8 states. Colorado and Utah require permits for harvesting rainwater, whereas Montana, North Dakota, South Dakota and Utah do not (USEPA Region 8 2016).

2.2.2.2. Resources

EPA Region 8 has compiled a list of resources on green infrastructure and LID. Some are general, whereas others are specific to locales in Region 8 or semi-arid and arid climates. The region-specific resources are described in Chapter 3 of this report under state and municipal/county policy initiatives and guidance (USEPA Region 8 2016).

Table 2-3. EPA Region 8 green infrastructure demonstration projects in the semi-arid west

Project	*Description*	*City*	*State*
Stapleton Greenway Park	Bioretention pond	Denver	CO
Bioretention pond	Bioretention pond	Fort Carson	CO
Stapleton Quebec Square shopping center	Bioswale	Denver	CO
South Platte River	Bioswale	Denver	CO
Vegetative swale	Bioswale	Fort Carson	CO
EPA Region 8 building	Green roof	Denver	CO
Denver Museum of Contemporary Art	Green roof	Denver	CO
Denver Botanic Gardens	Green roof	Denver	CO
REI Parking Garage	Green roof	Denver	CO
Church of Jesus Christ of Latter-Day Saints Conference Center	Green roof	Salt Lake City	UT
Denver Housing Authority	Permeable pavement	Denver	CO
South Platte River path	Permeable pavement	Denver	CO
Urban Drainage and Flood Control District	Permeable pavement	Denver	CO
Odell Brewery	Permeable pavement	Fort Collins	CO
CTL Thompson	Permeable pavement	Fort Collins	CO
Northern Plains Resource Council building	Permeable pavement	Billings	MT
Denver Housing Authority	Rain garden	Denver	CO
Environmental Center for the Rockies	Rain garden	Boulder	CO
Regis University	Rain garden	Denver	CO
Stapleton soft running path	Rain garden	Denver	CO
TAXI Development	Rain garden	Denver	CO
New Belgium Brewery	Rain garden	Fort Collins	CO
University of Utah	Rain garden	Salt Lake City	UT
Antiques Central	Rain garden	Cheyenne	WY

Source: USEPA Region 8 (2016).

2.2.3. Region 9

EPA Region 9 supports the use of green infrastructure to reduce stormwater runoff, entrainment of pollutants in runoff, and discharge of pollutants into receiving waters. Financial support for promoting the use of green infrastructure and LID in the Pacific Southwest is available from the Section 319 Nonpoint Source Management Program, which was established to support state, territory and tribal efforts to address nonpoint source pollution under Section 319 of the CWA; the Urban Waters Small Grants program; the Green Infrastructure Technical Assistance program; the Clean Waters Act State Revolving Fund; and the National Estuary Program. Examples of past projects funded by these opportunities in Mediterranean and semi-arid locations in EPA Region 9 are the Los Angeles River Street Biofiltration Project (Section 319 Nonpoint Source Management Program), the Redondo Beach Alta Vista Park Diversion and Reuse Project and Hermosa Beach Strand Infiltration Trench (Clean Water Act State Revolving Fund), and the Morro Bay National Estuary Program (National Estuary Program).

Regarding the use of green infrastructure and LID in MS4 permits, the cities of Long Beach and Salinas, California, renewed MS4 permits containing provisions requiring the use of LID. The city of Santa Monica updated its urban runoff pollution ordinance to require new development and redevelopment projects to use LID. The San Diego and Los Angeles County regional permits also include provisions requiring LID.

EPA Region 9 also has compiled material on LID in the Pacific Southwest, including reports from the Natural Resources Defense Council on rooftop rainwater harvesting (Garrison, Kloss and Lukes 2011) and addressing water resource and climate challenges in California (NRDC 2009); the California LID Portal (CSQA 2016), which was established by the California Stormwater Quality Association and contains tools and other resources on LID; and a video by the California State Water Resources Control on slowing the flow of stormwater (CEPA 2016; USEPA Region 9 2016).

Chapter 3.
Policy Initiatives and Guidance to Address Drought and Water Sustainability Through Green Infrastructure

This chapter outlines policy initiatives and guidance that promote and help implement green infrastructure. At the federal level, direction to apply green infrastructure to improve federal sustainability has been provided by executive order. States in arid and semi-arid regions of the United States have issued guidelines on implementing green infrastructure practices. Municipalities and counties have developed implementation guidelines as well. In addition, implementation guidance has been developed through partnerships between academia, EPA regional offices and municipalities. Finally, nongovernmental agencies are active in promoting green infrastructure and LID in arid and semi-arid regions, mainly through advocacy and education.

3.1. Federal

Implementation of green infrastructure is part of recent federal initiatives to plan for sustainability. These activities build on the commitments made by federal agencies as part of the Green Infrastructure Collaborative.

3.1.1. Executive Order 13693

On March 19, 2015, President Barack Obama signed Executive Order (EO) 13693, *Planning for Federal Sustainability in the Next Decade*.[2] As part of the water and stormwater management goals of the EO, the head of each federal agency was directed to "improve agency water use efficiency and management, including stormwater management by … installing appropriate green infrastructure features on federally owned property to help with stormwater and wastewater management," beginning in fiscal year 2016.

3.1.2. Council on Environmental Quality

Under EO 13693, the Chair of The White House Council on Environmental Quality (CEQ) was directed to establish temporary interagency working groups to provide recommendations on implementing the goals of the order, including the goal of installing green infrastructure. The CEQ issued implementation instructions for EO 13693 on June 10, 2015 (CEQ 2015). The instructions cite Section 438 of the Energy Independence and Security Act of 2007 (EISA), which mandates that construction projects for new federal facilities with a footprint of at least 5,000 square feet "manage stormwater and preserve and/or restore natural site hydrology."[3] As a target for achieving the green infrastructure goal of EO 13693, the CEQ identifies implementation of green infrastructure and stormwater best practices on new federal construction projects to the maximum extent technically feasible, per EISA Section 438 requirements. As a second target, the CEQ encourages federal agencies to update the commitments they made to the

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[2] Exec. Order No. 13693, 80 *Fed. Reg.* 57 (Mar. 25, 2015).

[3] Energy Independence and Security Act of 2007, 42 U.S.C. § 17094 (2007).

Green Infrastructure Collaborative (GIC 2014a, 2014b) and develop plans to meet those commitments.

The implementing instructions cite the information that EPA has made available on its green infrastructure website (USEPA 2016b) regarding federal requirements for green infrastructure, as well as strategies to plan and implement green infrastructure projects. This information is described in detail in Chapter 2 of this report. In addition, the CEQ cites information and guidance on green roofs available from the U.S. General Services Administration (GSA 2015).

3.2. State guidance

Some states in arid and semi-arid regions of the United States have issued guidelines on implementing green infrastructure practices. These include a guideline for retrofitting streets, right-of-ways and parking lots issued by Arizona; a guidance for implementing LID practices allowed under an NPDES municipal stormwater permit in Washington; and rainwater harvesting guidelines issued by Texas.

3.2.1. Arizona

The Arizona Department of Environmental Quality collaborated with EPA to fund the development of *Green Infrastructure for Southwestern Neighborhoods* (MacAdam 2012). The manual provides guidelines for retrofitting existing neighborhood streets, right-of-ways and parking lots with green infrastructure practices. It describes the types of practices that can be implemented streetside (see Figure 3-1), in streets and in parking lots. Some of the problems addressed in the manual are unique to the Southwest, such as minimal shading by vegetation in streets and parking lots, the presence of degraded ephemeral channels called washes or arroyos that flow only periodically, low and variable precipitation, the tendency of the trunks and stems of many desert plants to rot when standing in water or where wet mulch lays against their trunks or stems for extended periods, and the design of many Southwest streets to convey stormwater. The manual includes information on creating a water budget for bioretention areas, using Tucson as an example. It also includes maintenance guidelines, such as using native, drought-adapted plants and climate-appropriate watering schedules, as well as pruning native trees and shrubs to natural growth forms.

Figure 3-1. A curb cut draws stormwater from the street into a bioretention basin in the right of way.

Source: MacAdam (2012). Photo credit: Watershed Management Group.

3.2.2. Washington

Washington State has developed an *Eastern Washington Low Impact Development Guidance Manual* (Carlson et al. 2013). The manual describes the varied climate of eastern Washington, the driest regions being the Central Basin, which averages 14 to 16 inches of precipitation annually, and the intermountain regions of Okanogan, Spokane, and the Palouse, which average 12 to 22 inches of precipitation annually. The climate regions of eastern Washington are shown in Figure 3-2.

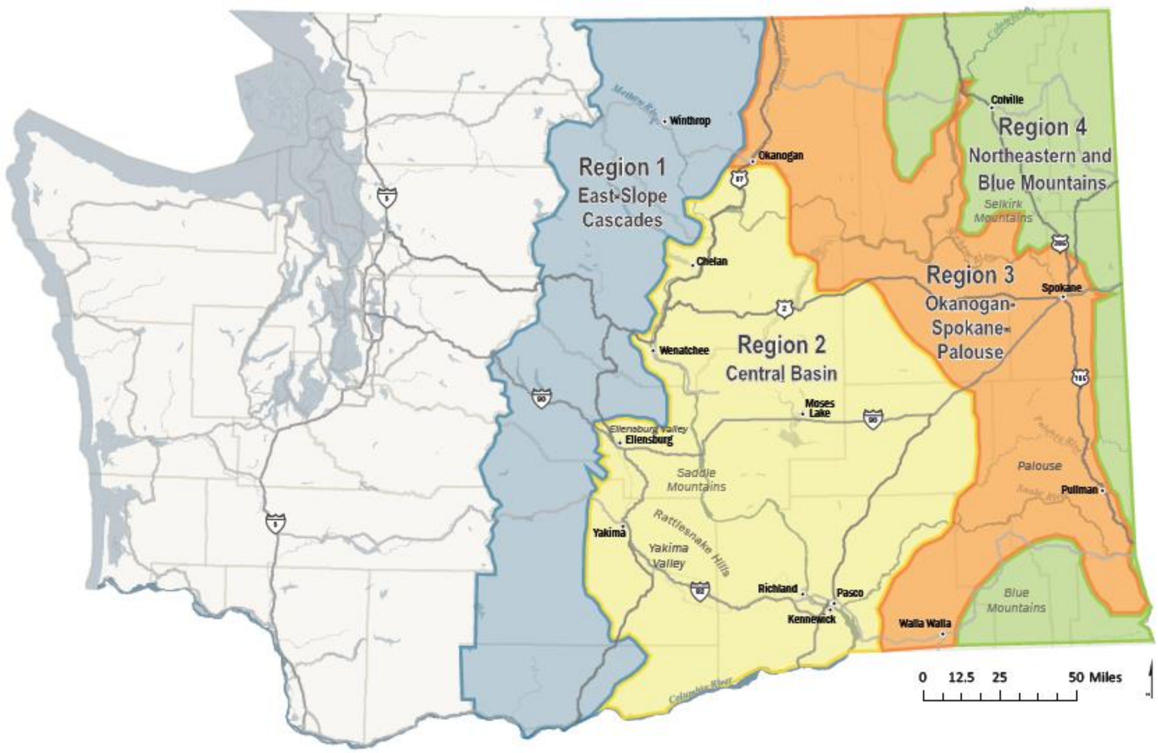

Figure 3-2. The climate regions of eastern Washington.

Source: Carlson et al. (2013).

Aridity and cold temperatures are design considerations in eastern Washington. The manual points out some of the unique considerations associated with arid and semi-arid regions, including intense, relatively infrequent storms; high evapotranspiration rates; sparse vegetation that leaves soil prone to erosion; and development patterns characterized by low density and large amounts of impervious surface area. Plant selection must consider tolerance for drought, extreme heat, and winter conditions that include snow cover and freezing.

In 2012, the Washington Department of Ecology issued the Eastern Washington NPDES Municipal Stormwater Permit, which takes steps toward implementing LID practices. The *Washington Low Impact Development Guidance Manual* is a tool to provide local jurisdictions with design guidance to implement the LID projects allowed under the permit. The manual describes the planning and design process for LID projects. LID BMPs—including the green infrastructure BMPs of bioretention, trees, vegetated roofs, and permeable pavement rain harvesting—also are described and design criteria are presented. In an appendix, the manual provides a list of native and nonnative trees, shrubs, grasses, perennials, wildflowers and groundcover suitable for use in bioretention projects in eastern Washington.

3.2.3. Texas

The Texas Water Development Board has prepared the *Texas Manual on Rainwater Harvesting* (TWDB 2005). The manual includes information on rainwater harvesting system components; water quality and treatment; system sizing; guidelines on best practices, building codes, cistern design and backflow prevention; cost estimation; and tax and other financial incentives. Rainfall data for representative Texas cities and case studies also are included. The manual recognizes that rainfall in some parts of Texas may not be sufficient to meet domestic needs (see Figure 3-3).

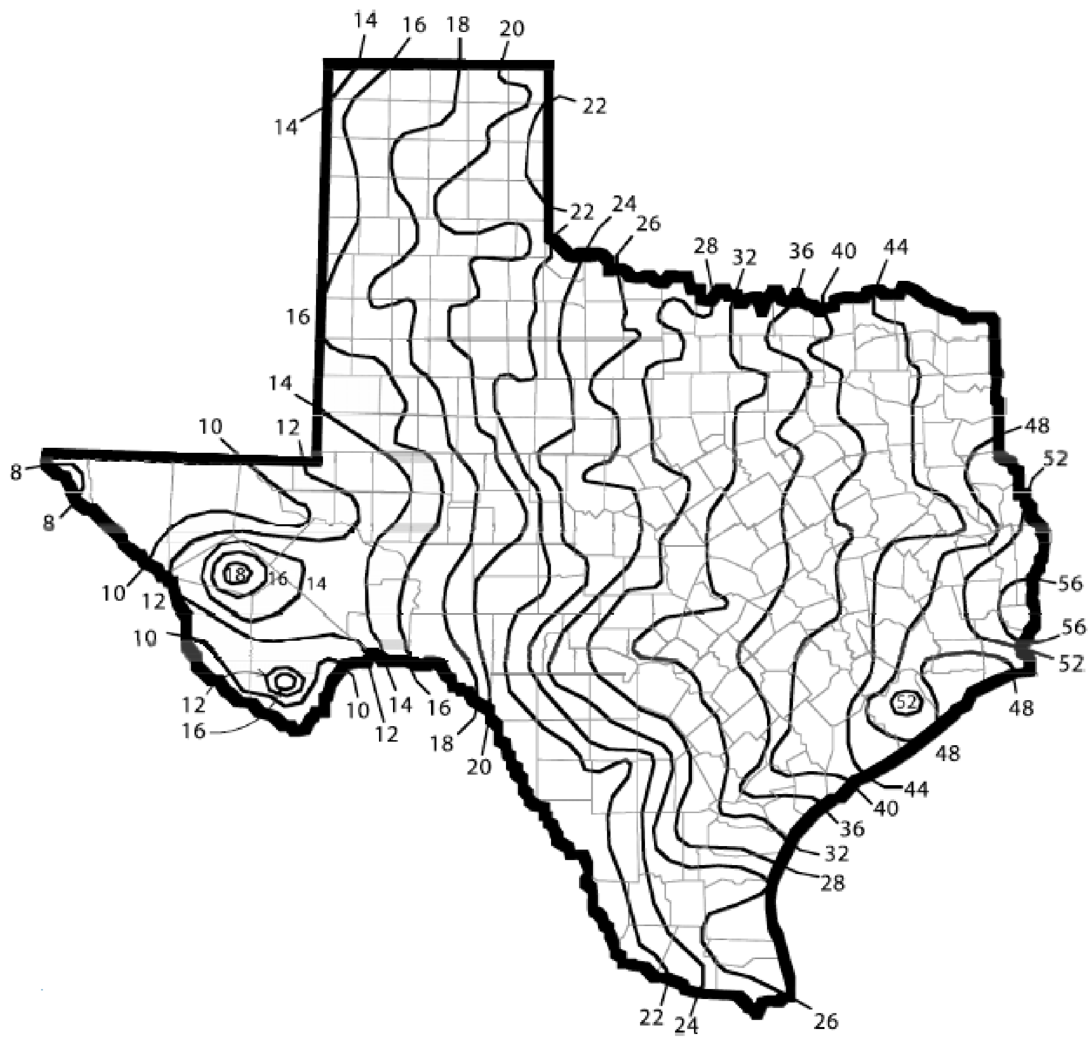

Figure 3-3. Average annual precipitation in Texas, in inches.

Source: TWDB (2005).

Municipal/county guidance

Municipalities and counties in the semi-arid and arid regions of the United States have issued guidance on implementing LID and green infrastructure practices tailored to local climate and conditions, including local topography and geography. Design and maintenance considerations include the existence of wet and dry seasons, hot and arid conditions that require drought-tolerant vegetation, and site-specific hydrology.

3.2.4. Denver, Colorado

Denver has issued guidance on aesthetically enhancing detention and water quality ponds (Mancini et al. 2010). The guide is intended for design professionals so that aesthetic elements may be incorporated into projects in the early stages of design and cites the advantages of green infrastructure in reducing and delaying stormwater runoff volumes, as well as reducing pollutants in stormwater. The guide includes tools on siting and functionality, physical character and architectural elements, and landscape design to enhance sites.

3.2.5. Los Angeles, California

The city of Los Angeles has issued the *Development Best Management Practices Handbook, Part B: Planning Activities* (City of Los Angeles 2011) to reflect the LID requirements that took effect on May 12, 2012. The purpose of the handbook is to assist developers in complying with the requirements of the Development Planning Program regulations of the city's stormwater program. Its target audience is developers, designers, contractors and homeowners, as well as city staff members who are engaged in plan checking, permitting and inspections related to land development activities. The handbook provides background material, including the legal framework behind incorporating LID BMPs into stormwater management; describes the project review and permitting process; presents information on stormwater management measures; provides guidance on BMP prioritization and selection; and describes offsite mitigation measures.

The handbook specifies the prioritization and selection of BMPs. The prioritization of BMPs is (1) infiltration systems, (2) stormwater capture and use, (3) high efficiency biofiltration or bioretention systems, and (4) a combination of any of the aforementioned BMPs. Infiltration feasibility screening and capture and use feasibility screening criteria are provided in the handbook. Design specifications for infiltration and capture and use BMPs also are presented. Among the design requirements is a specification that drought and flood resistant plant species native to California be selected when possible.

3.2.6. Pima County, Arizona

Tucson and Pima County produced a technical guidance for the use of LID and green infrastructure throughout Pima County (City of Tucson 2015). It is intended for the professional community and provides information on the site assessment, planning and design process; specific LID site planning practices; structural green infrastructure practices; and common green infrastructure components. Appendices include an analysis of University of Arizona rainfall data, sizing features to support vegetation based on University of Arizona evapotranspiration and rainfall data, design volume calculations based on University of Arizona rainfall data to size green infrastructure and LID practices, and a list of plants recommended for the hot and dry conditions of the desert Southwest.

3.2.7. San Diego, California

The *San Diego Low Impact Development Design Manual* (Tetra Tech 2011) provides guidance to ensure that project designs effectively carry out the goal of stormwater regulation and are reliable and cost-effective to maintain. The manual includes information on site assessment, planning and design; LID selection; implementation considerations; and appendices on BMP sizing, design guidance and templates, fact sheets, recommended plants, and inspection and maintenance.

Region-specific guidance related to the local climate, topography, hydrology, surface water and soils is provided. This includes suggestions to incorporate native vegetation or vegetation that is resilient to water shortages and periodic flooding into LID practices; mimicking typical predevelopment hydrology, which was characterized by the formation of vernal pools by smaller storms and water from larger storms flowing through canyons; increasing dry-weather base flows in streams and rivers to improve surface water quality; and accounting for the clayey soils of the region when conducting analyses of infiltration for LID practices.

3.3. Collaborative guidance

A design manual for green roofs in arid and semi-arid regions is an example of a multistakeholder collaboration. *Design Guidelines and Maintenance Manual for Green Roofs in the Semi-Arid and Arid West* (Tolderlund 2010) was produced through a collaboration of Green Roofs for Healthy Cities, the City and County of Denver, EPA Region 8, the Urban Drainage and Flood Control District, and Colorado State University. Some of the challenges identified for green roofs in arid and semi-arid regions are low annual precipitation, low average relative humidity and high solar radiation. These challenges require consideration of specific design strategies, plant selection, growing media and supplemental irrigation requirements. The manual provides recommendations and requirements regarding green roof design, implementation and maintenance for arid and semi-arid regions. It is intended for use by professionals and local jurisdictions. It presents information on design and implementation, leak detection, integration of solar panels on green roofs, insurance and liability, maintenance, costs, and case studies.

3.4. Nongovernmental agency guidance

Nongovernmental agencies are active in promoting green infrastructure and LID in arid and semi-arid regions. Examples are Amigos de los Rios, AridLID.org, the Council for Watershed Health, and the Watershed Management Group.

Amigos de los Rios works in East County Los Angeles to protect and restore open spaces. It specializes in developing parks in park-deficient neighborhoods using LID landscape practices. Some of the green infrastructure practices used by Amigos are on-site water filtration, bioswales and low-water-use irrigation, as well as drought-tolerant and native-plant landscaping (Amigos de los Rios 2016).

AridLID.org is a website that provides information and resources on LID in arid environments, particularly the southwestern United States. It is administered by the Ciudad Soil and Water

Conservation District, a political subdivision of the state of New Mexico that has among its responsibilities control and prevention of soil erosion, prevention of sediment and floodwater damage, and conservation of water. Originally, it was the website of the *2010 Albuquerque Area Green Infrastructure & Low Impact Development Workshop*, and it catalogs presentations of past Arid LID Conferences (Ciudad Soil and Water Conservation District 2016).

The Council for Watershed Health initiated the Water Augmentation Study (WAS), a long-term research project to explore the potential for increasing local water supplies in the Los Angeles region and reducing urban runoff pollution by increasing infiltration of stormwater runoff. The study currently is developing a regional strategy for developing stormwater as a new source of water for southern California (Council for Watershed Health 2015b).

The Watershed Management Group focuses on improving desert ecosystems. It is based in Tucson and works in the Phoenix Valley, other southern Arizona communities, and the border region between Arizona, United States, and Sonora, Mexico. It provides educational programs, offers water-harvesting landscape services, and engages in advocacy and stewardship to restore local rivers (Watershed Management Group 2015).

Chapter 4.

Current Research in the Application of Green Infrastructure for Stormwater Management and Conservation in Arid and Semi-Arid Regions

A literature survey was conducted to determine the state of the science for the application of green infrastructure to manage and conserve stormwater in arid and semi-arid regions. In this chapter, effects on water quality, stormwater infiltration, water conservation and habitat preservation, as well as design optimization and economic benefits, are described. The information is presented first for BMPs used principally for managing stormwater to increase infiltration close to the source of precipitation, and then for BMPs that conserve stormwater so that it can be used to reduce potable water demands. Research on the stormwater management BMPs has been performed at the scale of individual sites and watersheds, including monitoring and modeling studies.

4.1. Methodology

A survey of the recent literature (2010–2016) was conducted to report on the current state of the science for the application of green infrastructure practices in stormwater management and conservation. Terminology for green infrastructure BMPs is not standardized; therefore, the literature search was conducted using the various terms of art used to describe each of the practices (e.g., "permeable pavement," "pervious concrete"). The geographic scope of the literature review included U.S. and international field studies conducted under arid or semi-arid conditions, as well as modeling studies of arid and semi-arid conditions (Köppen-Geiger Climate Classification Group B). The geographic scope also included investigations conducted in Mediterranean climates (Köppen-Geiger climate classifications Csa and Csb), which are typified by a prolonged dry summer season, making the results of such studies applicable to xeric climates. The climate zones for field and modeling study sites were confirmed using an online database (CantyMedia 2016).

4.2. Stormwater management—site-scale research

Site-scale BMPs have been evaluated in arid, semi-arid and Mediterranean climates for management of stormwater quantity and quality. Practices have been tested for their ability to improve the quality of stormwater, including sediment, nutrients, bacteria, pesticides and other organic compounds, and metals. The ability of vegetation to sequester carbon and nitrogen also has been assessed. In addition, the role of BMPs in preventing soil erosion has been investigated. For practices that use soil substrates, leaching of nutrients has been quantified. The ability of BMPs to reduce runoff is a key performance parameter that has been evaluated under different precipitation regimes. Field and modeling studies have been conducted to optimize BMP design for climate and hydrological conditions found in dry regions. Maintenance needs, primarily irrigation, have been tested.

4.2.1. Bioswales

The effects of bioswales on stormwater runoff quality have been assessed under Mediterranean climate conditions. The practice has been tested for removal of fecal bacteria and effects on nutrient loading. The effects of bioswales in sediment removal have been evaluated as part of an integrated bioretention system as described in the discussion of David et al. (2015) below.

4.2.1.1. Water quality improvement

The ability of bioswales to remove bacteria was assessed in a Mediterranean climate. As part of California's Clean Beach Initiative, a vegetated wetland swale in Pacifica, California, was constructed and tested for its effect on the loading of fecal indicator bacteria to beaches. The swale reduced bacterial densities post- versus pre-project for total coliforms, fecal coliforms and enterococci at shoreline sampling stations up to fourfold, but these results were not statistically significant (Dorsey 2010).

4.2.1.2. Negative effects on effluent water quality

The effects of a high-capacity vegetated swale on effluent water quality of highway runoff were measured recently in Santa Barbara, California, a Mediterranean climate. Orthophosphate concentrations frequently were higher in effluent than influent, which the authors attribute to possible leaching from plants (Jiang, Yuan and Piza 2015).

4.2.2. Green roofs

Research on adapting green roofs for use in arid and semi-arid regions has focused on categorizing their performance in sequestering carbon and nitrate, assessing possible negative impacts on runoff water quality, and optimizing stormwater retention. Design challenges for dry climates include selecting plants that will grow under harsh conditions of heat and drought, evaluating irrigation needs, optimizing substrate depth for weight and ability to support plant growth, selecting the appropriate growth media, adding natural or artificial amendments to the growth medium to increase water retention and enhance plant growth, considering the thermal properties of the growth medium, and optimizing roof slope.

4.2.2.1. Carbon and nitrogen sequestration

The ability of green roofs to affect climate change by sequestering carbon has been studied in semi-arid regions. Carbon and nitrogen sequestration potential of green roofs was found to depend on the inorganic component of green roof substrates, as well as plant species, and varied widely, with some substrates acting as net exporters of carbon and nitrogen over the course of the 10-month experiment in a semi-arid region of Spain (Ondoño, Martinez-Sanchez and Moreno 2016b). In a separate study, carbon and nitrogen fixation by the substrate and aboveground plant material was higher in soil-amended substrates in simulated green roofs in a semi-arid region of southeast Spain (Ondoño, Martinez-Sanchez and Moreno 2016a).

4.2.2.2. Leaching from substrate

Rather than acting as sinks for carbon and nitrogen, green roofs can act as sources of contaminants to stormwater runoff. In a review of the performance of field-scale LID/green infrastructure systems in arid and semi-arid climates, the authors noted that although green roofs have shown potential in reducing such pollutants as nitrogen and phosphorus because of microbial processes and plant uptake, studies have shown conflicting results, particularly for nitrogen (Jiang, Yuan and Piza 2015). In a laboratory microlysimeter study comparing compost and peat amendments to green roof substrates, nitrate leaching on first flush was high for some types of compost amendments, but peat and garden waste compost exhibited minimal nitrate leaching (slightly above 10 mg L^{-1} nitrate nitrogen), and the first flush only lasted for the first 50 to 100 mL effluent volume (Ntoulas et al. 2015). Contaminant concentrations in runoff were shown to decrease over time in a 9-month study of the water quality of outflow from intensive and extensive green roof systems in the Mediterranean climate of Adelaide, Australia. Parameters such as pH, turbidity, nitrate, phosphate and potassium were higher in outflows from intensive green roofs, however, compared with outflows from extensive green roofs (Razzaghmanesh, Beecham and Kazemi 2014b). In another study in Adelaide that focused on the effects of vegetation on outflow quality, pilot-scale green roofs were found to be a source of pollutants, including salt, nitrate, nitrite, ammonia and orthophosphate, although vegetated green roofs generally had better outflow quality than nonvegetated control beds. For vegetated beds, the outflow water quality from intensive green roofs was better than from extensive green roofs. Growing media with less organic matter had better outflow water quality (Beecham and Razzaghmanesh 2015).

4.2.2.3. Stormwater retention

The effects of organic material amendments to substrates have been tested, comparing different types of organic amendments for their physicochemical properties (i.e., porosity and water retention capacity). In laboratory tests comparing peat with several types of compost amendments available locally in a semi-arid environment, peat-amended substrate was found to have increased moisture retention (Ntoulas et al. 2015).

The physicochemical properties of different inorganic substrate components have been compared. In an investigation using "cultivation tables" in a semi-arid region of southeast Spain, substrates made from compost-amended mixtures of silica, crushed bricks and clay-loam soil were compared for physicochemical properties (i.e., water retaining capacity and porosity). Compost-amended substrates containing sand or soil and crushed bricks were determined to have acceptable water retaining capacity and high porosity (Ondoño, Martinez-Sanchez and Moreno 2016b).

The effect of vegetation on the water retention capacity of green roofs has been evaluated under Mediterranean climate conditions. In a 2-year study of model green roofs in Adelaide, Australia, vegetation increased water retention by intensive and extensive green roof beds compared with nonvegetated controls. The authors attributed this affect to the role of evapotranspiration in increasing the stormwater retention capacity of green roofs, particularly for longer antecedent dry weather periods (Beecham and Razzaghmanesh 2015). In Corvallis, Oregon, vegetated roofs had significantly higher retention capacity during the dry summer than medium-only roofs. Irrigation significantly decreased the retention capacity of vegetated and medium-only roofs during the summer. During the rainy season, vegetation had no effect on stormwater retention (Schroll et al. 2011).

The hydrologic response of green roofs has been evaluated in a Mediterranean climate. Researchers comparing intensive and extensive systems with different media type found the only significant difference between intensive versus extensive systems was in peak attenuation and peak runoff delay, which were higher for intensive green roofs (Razzaghmanesh and Beecham 2014).

Longer dry periods and warmer seasons tend to increase water retention. Factors that affected retention performance and runoff volume in a Mediterranean climate were rainfall depth, intensity and duration, as well as the average dry weather period between rainfall events (Razzaghmanesh and Beecham 2014).

Stormwater retention performance of green roofs has been assessed under semi-arid conditions. A field-scale green roof in Denver with a 45 percent impervious cover had a 68.7 percent average runoff reduction rate over 3 years. Rainfall retention performance has been shown to decrease, however, with increasing rainfall amounts (Jiang, Yuan and Piza 2015).

4.2.2.4. Design optimization for plant establishment and growth

Green roofs have been characterized as hostile environments for plant growth because of factors that include shallow substrate depth, high temperatures, lack of shade and wind exposure. Different plants have different hydraulic responses to drought stress. In the Mediterranean climate of Messina, Italy, an anisohydric species (e.g., *Salvia officinalis*) and an isohydric species (e.g., *Arbutus unedo*) both were determined to be appropriate for a green roof installation, but in experiments using extensive green roof modules, the water status of the two types of plants was shown to depend on the water retention properties of the substrate, with anisohydric species requiring an appropriate substrate (Raimondo et al. 2015). Comparing indigenous Australian ground cover and grass species in prototype-scale green roofs in Adelaide, Australia, a Mediterranean climate, researchers showed that the succulent species best tolerated the hot, dry summer conditions in terms of growth and water use efficiency (Razzaghmanesh, Beecham and Kazemi 2014a). Higher water use plants have been shown to die sooner under simulated drought conditions than conservative water users, with survival being related to reduced biomass under drought rather than increased leaf succulence (Farrell et al. 2012). Facultative crassulacean acid metabolism plants, which can switch from low transpiration during dry periods and high transpiration during rain events, or plants with a broad soil water niche have been recommended for extensive green roofs in hot climates. Facultative mycorrhizal grasses have been proposed as an alternative to sedum species, some of which fix carbon dioxide weakly above 20°C because of their temperate origins. Another alternative is a “brown roof”—planted with annual seeds, bulbs or other cryptophytes—that simulates desert conditions and is dormant during the dry season (Simmons 2015).

The need for irrigation of green roofs in dry conditions has been investigated. Different irrigation regimes have been tested with drought-resistant plants. Under Mediterranean conditions in Athens, Greece, a sedum species (*Sedum sediforme*) was established in experimental plots with high versus minimal irrigation during summer drought periods in the first year. The sedum was able to survive in its second year without irrigation (Nektarios et al. 2015). An investigation in a semi-arid region of southeast Spain found, however, that the two species of Mediterranean plants tested required irrigation during drought conditions in a 9-month trial (Ondoño, Martinez-Sanchez and Moreno 2016a). A study of indigenous Australian species in prototype-scale extensive and intensive green roofs in Adelaide, Australia, a Mediterranean climate, showed that some plants required supplementary irrigation during the hot, dry summer (Razzaghmanesh, Beecham and Kazemi 2014a). In a review of adapting green roof irrigation practices for sustainable water management, the authors advised installing an irrigation system in arid climates to keep the vegetation alive during dry periods or leaving the roof unvegetated during the summer, although the cooling benefits of vegetation then are lost (Van Mechelen, Dutoit and Hermy 2015).

To optimize water usage, incorporating wastewater or recirculated water resources is a green roof design option for arid and semi-arid areas. Because these water resources tend to have higher salinity than fresh water, investigators tested the effects of salinity on growth of *Lobelia erinus*, a potential species for use in cover applications in green roofs, in a hydroponic system and determined that although growth was affected, salinities as high as 50 mM sodium chloride did not produce toxic effects on the leaves (Escalona et al. 2013).

Substrate depth has been found to affect growth of vegetation under seasonally dry and semi-arid conditions. Sedum growth in Athens was enhanced in deeper substrates under no-irrigation conditions, although plants were able to survive even with a shallow substrate depth (Nektarios et al. 2015). In a 2-year study of turf cover of an extensive green roof system by *Paspalum vaninatum* turfgrass in Athens, the use of a deeper substrate (15 cm) reduced irrigation needs (Ntoulas and Nektarios 2015). For Manilagrass (*Zoysia matrella*), which was tested using a simulated green roof in Athens, greater substrate depth was found to be more important than substrate formulation in reducing drought stress under water deficit conditions (Ntoulas et al. 2013). Deeper substrates produced greater rates of plant growth and aboveground biomass production in experiments in a semi-arid region of southeast Spain (Ondoño, Martinez-Sanchez and Moreno 2016a). In an Australian study in a Mediterranean climate, the greater substrate depths characteristic of intensive as opposed to extensive green roofs produced the best growth (Razzaghmanesh, Beecham and Brien 2014). Greater substrate depth (15 cm vs. 7.5 cm) was found to promote growth and increase leaf dry weight during a drought period in a study using *Dianthus fructicosus* in a Mediterranean climate (Nektarios et al. 2011).

The applicability of soil and soil-less substrates has been compared under seasonally dry conditions. In a study of the growth of *Sedum sediforme* established in extensive green roof systems under Mediterranean climate conditions, using soil-amended versus soil-less substrate did not affect growth or physiology after the first year (Nektarios et al. 2015). During a drought period, substrate moisture was increased, however, in a soil-containing substrate as compared to a soil-less substrate, and a soil substrate showed higher growth during establishment (Nektarios et al. 2011). A study of the suitability of a native Mediterranean xerophyte for use on extensive green roofs in a Mediterranean climate found that growth and flower number was promoted in a soil-containing versus a lighter soil-less substrate, although the effect was not large (Tassoula et al. 2015). The hydrolytic enzyme activity, which is linked to nutrient cycling, was highest in soil-containing green roof substrates in simulated green roofs in a semi-arid region of southeast Spain (Ondoño, Martinez-Sanchez and Moreno 2016b). In a separate study under semi-arid conditions, soil-amended substrate showed higher rates of microbial activity and nutrient cycling, necessary for plant development, compared with non-amended substrate (Ondoño, Martinez-Sanchez and Moreno 2016a).

The effects of organic material amendments to substrates have been tested under seasonally dry conditions, comparing different types of organic amendments for their ability to support growth. In a simulated green roof system in Athens, different types of organic material amendments were tested using Manilagrass. Compost-amended substrates supported the most growth under conditions of adequate irrigation but increased drought stress during water deficit periods. Peat amendments, combined with deeper substrate, performed better than compost in supporting growth under water-deficit conditions (Ntoulas et al. 2013). For *Paspalum vaginatum* turfgrass in extensive green roofs in a Mediterranean climate, compost amendments increased turf cover under water-sufficient but not water-deficient conditions (Ntoulas and Nektarios 2015). Supplementing the growth medium with 50 percent organic compost produced more vigorous growth compared to two commercially available media under dry climate conditions (Razzaghmanesh, Beecham and Brien 2014).

Industry guidelines that specify a large fraction of porous, mineral-based materials in the growing media (FLL 2008), although appropriate for temperate regions, may not be optimal in dry climates. The choice of the inorganic component of green roof substrates has been shown to affect plant growth. In an investigation of substrates made from compost-amended mixtures of silica, crushed bricks and clay-loam soil, plant growth patterns on the different inorganic substrates under semi-arid conditions varied by species (Ondoño, Martinez-Sanchez and Moreno 2016b). A 12-month study of growth responses of Australian native plants on medium-scale green roofs in Adelaide, Australia, showed that some commercially available media were able to sustain little growth in a seasonally dry, Mediterranean climate (Razzaghmanesh, Beecham and Brien 2014).

Substrate additives that increase water retention have been tested for their ability to increase drought resistance and expand plant selection for green roof vegetation in dry climates. These substrate additives have an advantage over soil in that they increase water retention but do not decompose over time (Simmons 2015). In a controlled greenhouse environment, a polyacrylamide water-absorbent gel increased the substrate water holding capacity by 24 percent, increasing shoot growth (Young et al. 2014). During a greenhouse simulation of a 25-day drought, polyacrylamide gel was more effective than a sedum living mulch in increasing the tested species' drought tolerance (Young, Cameron and Phoenix 2015). In greenhouse and laboratory studies, green waste biochar was shown to delay the time to reach the permanent wilting point for the test plant, winter wheat (*Triticum aestivum*), and increase the substrate water holding capacity (Cao et al. 2014). Silicate granules and hydrogel, however, had differing effects on plant-available water for winter wheat and white lupin (*Lupinus albus*) in simulated drought greenhouse experiments (Farrell, Ang and Rayner 2013). Substrates with higher water retention increased plant survival times under simulated drought conditions (Farrell et al. 2012).

In addition to the water retention properties of growth medium, thermal conductivity and heat capacity can be a concern. Summer temperatures exceeding 70°C have been recorded on roof surfaces in Texas, which exceeds the heat tolerance of roots even for arid-adapted crassulacean acid metabolism plants and may limit plant growth. Green roof growth media have not been designed for hot, dry climates. A clay-based commercially available growth medium was shown to have high heat capacity in laboratory trials (Simmons 2015).

The effects of roof slope on growth performance have been evaluated under seasonally dry conditions. Mildly sloping roofs (1% slope) supported better plant growth than steep roofs (25%

slope) in a study conducted in Adelaide, Australia, a Mediterranean climate (Razzaghmanesh, Beecham and Brien 2014).

4.2.2.5. Design optimization for water retention

Optimizing the growing media depth and substrate water retaining capacity, considering the addition of a water storage layer, and the site's precipitation patterns are factors that can affect green roof design for arid and semi-arid climates. Green roof design has the conflicting goals of optimizing drainage to improve stormwater retention and retaining sufficient moisture to support plant survival. The effects of design parameters on a hypothetical green roof were modeled using the EPA's SWMM LID module with rainfall records for semi-arid Billings, Montana. The runoff reduction rate increased with growing media depth and water retaining capacity. The same green roof was found to have a higher runoff reduction rate in a semi-arid area than a humid area (Atlanta, Georgia), but it required more irrigation (Guo, Zhang and Liu 2014). In a modeling study of green roof performance in a semi-arid environment, adding a storage layer was found to increase the runoff reduction rate and reduce the need for irrigation (Guo, Zhang and Liu 2014). In an evaluation of the hydrologic response of green roofs in a Mediterranean climate, a nonlinear relationship between rainfall and runoff was found. The results of the study indicate that continuous time series modeling is more appropriate than peak rainfall intensity for green roof design (Razzaghmanesh and Beecham 2014). The use of a layer of hydroponic foam in place of a standard retention layer to increase water retention while making stored water available to vegetation has been tested successfully in Texas (Simmons 2015). In an established extensive green roof in Athens, substrate moisture was found to depend on the slope of the roof and presence of underground retaining walls, which increased substrate moisture. Substrate moisture was not affected by the type of draining system (geotextile or sand-gravel bilayer) or the substrate depth (300 mm to > 1,200 mm)—except in a relative flat area between the concert hall and the atrium of the roof—but varied because of local inclinations and sunlight exposure. Substrate moisture measurements taken 3 and 10 years after installation showed that the drainage system was functioning well (Nektarios et al. 2014).

4.2.3. Permeable pavement

The ability to manage stormwater runoff using permeable pavements in semi-arid regions has been the subject of modeling studies. Research also has focused on the improvement of the quality of stormwater by permeable pavement in the field under semi-arid and Mediterranean climate conditions. In addition, the effects of laboratory-simulated freeze-thaw cycling, traffic wear and laboratory-simulated clogging on infiltration capabilities of permeable pavement have been assessed relative to rainfall patterns typical of semi-arid areas.

4.2.3.1. Stormwater retention

The ability of permeable pavement to reduce stormwater runoff has been tested in the field and modeled in semi-arid environments. In a study in Denver, permeable interlocking concrete pavement reduced runoff volume by 33 percent, and pervious concrete pavement reduced runoff volume by 38 percent, compared to a reference site (Jiang, Yuan and Piza 2015). A modeling study evaluated the implementation of LID practices on a university campus with 40 percent impervious surfaces in semi-arid Tianjin City, China, using 10 years of past precipitation data. The researchers focused on smaller precipitation events (i.e., less than 1-inch rainfall depth, which represents approximately 77 percent of all events) and found that among the LID practices modeled, porous pavement performed best in three measures of water balance: the change in total runoff, the rainfall captured by LID on site, and the ratio of saved rainfall on site. It also reduced peak flow by 29 percent, second in performance only to bioretention (Huang et al. 2014). High-resolution satellite imaging data were used to extract land cover information for modeling the performance of porous pavement in a residential area of San Clemente, California, a Mediterranean climate. Porous pavement was estimated to reduce runoff volume by 18 percent (Khin et al. 2016). To evaluate the performance of permeable pavements to control runoff in a semi-arid region, the permeability of experimental test sections of different types of permeable pavement was measured using the ASTM C1701 method. Interlocking concrete pavers had the highest permeability (0.5 cm s^{-1}) and permeable asphalt pavements the lowest (0.1 cm s^{-1}), but all permeable pavements had permeabilities adequate to prevent surface runoff during typical rain events in central California (Li et al. 2013).

Parameters other than pavement permeability need to be considered in designing permeable pavement for stormwater retention. Researchers measured the hydraulic properties of subgrade soil and permeable pavement material in the laboratory and conducted numerical simulations for 24-hour rainfall data from 2-, 50- and 100-year storms in three rainfall regions of California. Sensitivity analyses revealed that the saturated hydraulic conductivity of subgrade soil was the most important parameter for the design of permeable highway shoulder retrofits to capture rainfall runoff (Chai et al. 2012).

The applicability of models to assess performance and design of permeable pavement under semi-arid field conditions has been tested. A field test conducted in Denver of the theoretical paved area reduction factor for porous pavement compared to measured rainfall events using EPA’s SWMM model found that the reduction factors are accurate and applicable to the Denver area (Blackler and Guo 2014).

4.2.3.2. Water quality improvement

Permeable pavement has been tested for its ability to improve of the quality of stormwater runoff in field studies. In Denver, runoff from a permeable interlocking concrete pavement site had significantly lower levels of zinc, chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and total suspended solids (TSS) compared to a reference site; runoff from a porous asphalt site had significantly lower nitrate plus nitrite and total selenium; and runoff from a pervious concrete site had significantly lower TSS, total phosphorus, TKN, COD and copper (Jiang, Yuan and Piza 2015). A study comparing permeable and conventional pavement systems installed in a parking lot in Adelaide, Australia, a Mediterranean climate, showed that permeable pavement improved stormwater quality significantly, reducing nutrient levels (i.e., total nitrogen and total phosphorus), heavy metals (i.e., zinc, lead, copper, cadmium and nickel) and TSS. The authors attributed the reduction of pollutant levels to mechanical filtration (Beecham, Pezzaniti and Kandasamy 2012).

4.2.3.3. Performance characteristics

Performance characteristics of permeable pavement have been assessed in semi-arid regions. In cold arid and semi-arid regions, degradation of pervious concrete by freeze-thaw cycling is a possible concern for soil-clogged or water-saturated conditions. An experimental pervious concrete slab in northern Utah was damaged at a significantly faster rate when clogged (i.e., failure at 93 freeze-thaw cycles versus 180 cycles) or saturated with water (i.e., failure at 80 freeze-thaw cycles versus 180 cycles). No significant differences in structural properties between clogged and unclogged locations were observed, however, which was attributed to only the upper 1 to 2 inches being filled with debris and the remaining depth of the slab being free draining (Guthrie, DeMille and Eggett 2010).

Clogging would be expected to decrease water retention and water quality improvement capabilities of permeable pavement as it ages. The effect of traffic volume-induced deterioration on infiltration performance was evaluated in a case study of deteriorated pervious concrete installed in a parking lot in Denver. The researchers found that the infiltration rate of the pervious concrete was decreased in high-traffic areas compared with low-traffic areas. Comparing the infiltration rates to estimated rainfall intensity in the metropolitan Denver area, all but the most high-traffic area would be expected not to have stormwater drainage problems up to a return period of 10 years (Kim et al. 2015). Laboratory testing of a pervious concrete pavement system clogged with sand and clay revealed that the pervious concrete system still would be effective for stormwater detention under conditions that might be encountered in semi-arid regions (i.e., the 100-year, 1-hour design storm for Denver), although the flow-limiting layer in these tests was found to be the subgrade, not the pervious concrete (Coughlin, Campbell and Mays 2012). In a study of pervious concrete pavements in parking lots that included sites in semi-arid regions of California, the age of the pavement was the main factor affecting measured permeability, and the mass of fine particles less than 38 μm also was an important factor. The porosity of the top surface layer of core samples generally was lower, indicating the importance of a regular cleaning maintenance program to improve porosity. The field measurements were conducted with a National Center for Asphalt Technology (NCAT) field permeameter (Kayhanian et al. 2012).

4.2.4. Planter boxes

Treatment and retention of stormwater by prototype planter boxes—rain gardens with vertical walls and open or closed bottoms—have been tested under arid and semi-arid conditions. The technology’s effects on gray water quality and simulated stormwater runoff quality have been compared using vegetated and nonvegetated units. The effect of vegetation on stormwater retention has been explored under semi-arid conditions.

4.2.4.1. Water quality improvement

The ability of prototype planter box systems to improve the quality of gray water (residential wastewater without toilet and kitchen sources) was evaluated in a study conducted outdoors in the United Arab Emirates to assess the applicability of gray water-fed planter boxes for arid environments. In a 10-day trial, vegetative and nonvegetative systems performed almost equally well in improving gray water quality, including turbidity and total coliform bacteria, but the vegetative system was more effective in reducing sodium and COD (Chowdhury 2015). Pilot experiments were conducted in hot and semi-arid Bryan, Texas, using four planter box units, each measuring approximately 4 m^3 in volume, planted with shrubs, grass species specified for highways in Texas, native Texas grasses and Bermuda grass (*Cynodon dactylon*), respectively. A fifth unit was weeded regularly to provide a nonvegetated control. After 14 months of growth, during which the units were regularly irrigated, synthetic highway stormwater runoff was added to the boxes, simulating the mean 24-hour storm runoff for a drainage basin of 330 m^2. All of the units, vegetated and nonvegetated, removed lead, zinc, TSS and ammonia, although the shrub and control units were approximately twice as effective at removing TSS than the grass units (Li et al. 2011).

The ability of planter boxes to remove bacteria has been tested under semi-arid conditions. In a follow-up study to Li et al. (2011), the vegetated units were allowed to develop naturally outdoors without weed control for one summer. After a summer of vegetation succession, the ability of each unit to remove *Escherichia coli* (*E. coli*) added to influent potable water was assessed. The effluent was collected from drainage outlets installed at the bottom of the units. The nonvegetated control unit had the highest removal efficiency for *E. coli* (97%), followed by the shrub unit (88%) and three grass units (76%, 57% and 48% removal efficiencies). Although removal mechanisms for *E. coli* are not well understood, the authors suggested that given the relative size of the bacteria compared to the porous medium, adsorption is a more likely mechanism than filtration. The root growth, rooting depth and nutrient metabolism of different types of vegetation varied, which would have affected the retention times and pollutant removal performance of the different units (Kim et al. 2012).

4.2.4.2. Negative effects on effluent water quality

In the study by Li et al. (2011) of pilot planter box units tested with simulated stormwater, vegetated units, as well as a nonvegetated control unit, were shown to export pollutants. The vegetated units and nonvegetated control unit leached nutrients, resulting in higher concentration in the effluent than the influent for nitrate, total nitrogen and total phosphorus. The authors speculated that denitrification in the rhizosphere in the vegetated units might have reduced nitrate leaching relative to the nonvegetated control. Higher TSS concentrations in the effluent or acidic soil conditions from microbial activity might have contributed to the greater leaching of total phosphorus from the vegetated units. Copper also was higher in the effluent than the influent for the vegetated units but not the nonvegetated control.

4.2.4.3. Stormwater retention

The effects of vegetation on influent and effluent hydrographs for pilot planter box units was evaluated in a hot, semi-arid climate. The vegetation—shrubs and three types of grass seed mixes—was allowed to grow for 14 months prior to the experiment. The vegetated pilot units reduced peak flows (14.4% to 32.2%), but the degree of reduction was highest for the nonvegetated control unit (74.8%). Surface ponding occurred immediately in the nonvegetated control unit but only was evident after 1 hour of flow for the vegetated units. The detention time was much longer for the nonvegetated control unit (118.3 minutes) compared with the vegetated units (15.1 to 25.6 minutes) (Li et al. 2011). In the follow-up study to Li et al. (2011), the retention times of vegetated units (planted with different vegetation and allowed to undergo natural secession for one summer) and a nonvegetated control planter box unit were compared again. The nonvegetated control unit had the longest retention time (141.6 minutes), followed by the unit originally planted with shrubs (67.2 minutes) and the three units originally planted with grasses (16.2 minutes for Unit B, 42.6 minutes for Unit H, and 18.3 minutes for Unit N).

Changes in soil porosity and preferential flow paths from different patterns of root growth would be reflected in the retention times of the units (Kim et al. 2012).

4.2.4.4. Design optimization

The suitability of different vegetation species for planter boxes has been assessed empirically in a semi-arid environment. Only one of the three original shrub species planted in a pilot planter box unit, Texas sage (*Leucophylum frutescens*), was thriving after 14 months. In the pilot units seeded with different types of grasses (grass species specified for highways in Texas, native Texas grasses and Bermuda grass), vegetation compositions were similar after 14 months, dominated by Johnson grass (*Sorghym halepense*) and giant ragweed (*Ambrosia trifida*) (Li et al. 2011).

To reduce nitrate leaching, planter boxes might be constructed with a lower soil-to-compost ratio in the growth medium. Creating a permanent water saturation zone in the bottom might facilitate denitrification as well (Li et al. 2011).

4.2.5. Rain gardens/bioretention cells

Rain gardens/bioretention cells have the potential to improve of the quality of stormwater and also mitigate runoff velocity and volume in arid and semi-arid environments. Rain gardens have been evaluated in semi-arid climates as potential sources of nutrient pollution to runoff as well. Specific design requirements for xeric climates—including vegetation selection, inclusion of a storage layer, soil type, irrigation, sizing and siting—have been assessed.

4.2.5.1. Water quality improvement

A rain garden installed in a residential neighborhood in Lakewood, Colorado, and monitored for 3 years reduced mean TSS in the effluent to a mean of 51.3 mg/L from a mean of 264.3 mg/L in the influent. The median event-based concentration reduction rate from stormwater was 91 percent for TSS but varied by event percentile (i.e., −5% for a 5th percentile event to 98% for a 95th percentile event). The median event-based concentration reduction rates were positive for TKN; ammonia nitrogen; and total lead, chromium and antimony but negative (i.e., the median concentration was higher in the effluent than influent) for total phosphorus; dissolved phosphorus; and total copper, arsenic, beryllium, cadmium and selenium. Like TSS, the event-based concentration reduction rates for these analytes were negative for small storms (5th percentile) and positive for large storms (95th percentile), as shown in Table 4-1 (Jiang, Yuan and Piza 2015).

In a study in Salt Lake City, Utah, nutrient retention by bioretention cells with different vegetation communities—an irrigated wetland, an unirrigated upland vegetation community and no vegetation—was compared. Synthetic stormwater was used to simulate runoff to each cell from an impervious surface. All three cells retained phosphate mass significantly ($P < .01$ by analysis of variance [ANOVA]), retaining approximately 50 percent of the influent phosphate during the 12-month study. The wetland and upland cells retained total nitrogen. The wetland cell required irrigation by more than 12,000 L of water, however, during the dry summer. The authors suggested that for optimal nutrient retention by bioretention cells, greater upland vegetation density or irrigation of wetland communities by gray water would be sustainable

Table 4-1. Mean influent and effluent concentrations and event-based concentration reduction rates from a rain garden

Constituents	*Mean Influent*	*Mean Effluent*	*Event-Based Concentration Reduction Rate (%)*			
			5th	*Median*	*Mean*	*95th*
TSS (mg/L)	264.3	51.3	−5%	91%	63%	98%
NO_3 + NO_2 (mg/L)	0.7	2.1	−1327%	−128%	−559%	−5%
TKN (mg/L)	3.1	2.6	−363%	18%	−31%	70%
NH_3-N (mg/L)	0.7	0.0	−378%	96%	−28%	100%
Tot. P (mg/L)	0.4	0.7	−1947%	−133%	−494%	76%
Ortho-P (mg/L)	0.2	0.4	−844%	−252%	−269%	−99%
Diss. P (mg/L)	0.5	1.1	−1357%	−196%	−358%	49%
Tot. sol. P (mg/L)	0.1	0.4	−560%	−350%	−317%	−104%
Tot. Cu (µg/L)	16.6	23.4	−393%	−12%	−73%	63%
Tot. Pb (µg/L)	8.1	5.0	−503%	98%	−30%	100%
Tot. As (µg/L)	3.3	4.4	−139%	−100%	−112%	100%
Tot. Be (µg/L)	0.0	0.1	−100%	−100%	−33%	80%
Tot. Cd (µg/L)	0.1	0.2	−407%	−100%	−107%	100%
Tot. Cr (µg/L)	2.9	1.4	−170%	100%	32%	100%
Tot. Sb (µg/L)	0.4	0.5	−100%	32%	26%	100%
Tot. Se (µg/L)	0.1	0.1	−100%	−100%	−68%	11%

Abbreviations: TKN = total Kjeldahl nitrogen, TSS = total suspended solids.

Source: Jiang, Yuan and Piza (2015). Reprinted by permission of the authors. Copyright 2015 Jiang, Yuan and Piza.

solutions (Houdeshel et al. 2015). It was suggested that plant roots increase stormwater infiltration rates by creating macropores through root growth and turnover (Houdeshel, Pomeroy and Hultine 2012).

4.2.5.2. Negative effects on effluent water quality

Rain gardens have been evaluated in semi-arid areas as potential sources of nutrients to runoff. In three bioretention cells located in semi-arid Salt Lake City, each planted with different vegetation communities, only the wetland cell retained nitrate (38%), but the upland and control (nonvegetated) cells exported two and nine times more nitrate, respectively, than was added as synthetic stormwater (Houdeshel et al. 2015). A rain garden constructed in a residential neighborhood in Lakewood, Colorado, acted consistently as a source rather than a sink for nitrate plus nitrite, orthophosphate and total dissolved phosphorus (Jiang, Yuan and Piza 2015).

The water quality in constructed wetlands in an urban environment has been shown to be affected by the amount of impervious surface that drains to the wetland, as was the case for polycyclic aromatic hydrocarbons (PAHs) detected in water samples from urban wetlands in Lubbock, Texas (Heintzman et al. 2015).

4.2.5.3. Stormwater retention

In a rain garden draining 0.77 hectares of a residential community in Lakewood, Colorado, with an impervious area of 47 percent, the average runoff volume reduction rate ranged from 37 to 61 percent over 3 years (Jiang, Yuan and Piza 2015).

A modeling study was conducted in a low-rise residential area located in a Mediterranean climate (San Clemente) that used EPA's SWMM to assess performance. The results showed that implementing bioretention in right-of-ways and grassy areas in front of buildings reduced runoff volume by 37.1 percent (Khin et al. 2016).

4.2.5.4. Design optimization

The choice of vegetation in bioretention gardens can be tailored for xeric climates. Combining deep-rooted shrubs—which have taproots to access deep soil water—with grasses that produce extensive networks of shallow roots that interface with arbuscular mycorrhizal fungi—which increase nutrient-absorbing ability—is recommended for optimal drought tolerance. Combining warm season bunchgrasses with locally native shrubs is recommended for warm deserts (i.e., Arizona, western Texas, New Mexico and southern Utah—typified by precipitation falling as rain during the growing season), whereas a mixture of warm and cool season bunchgrasses planted with locally native shrubs and evergreens is recommended for cool deserts (i.e., the Great Basin and Intermountain West—typified by precipitation falling as snow in the winter or spring) (Houdeshel, Pomeroy and Hultine 2012).

In urban areas, impervious surfaces prevent infiltration of precipitation where it lands. Including a storage layer in the design of bioretention gardens allows a relatively large volume of water, draining from surrounding impervious surfaces, to infiltrate in a small footprint. Designing the storage layer to be oxygen-limited promotes denitrification (Houdeshel, Pomeroy and Hultine 2012). A demonstration garden in Salt Lake City is an example of a successful bioretention garden that included a storage layer in which the vegetation was growing well without irrigation two summers after establishment. Successful plant species included regionally native bunchgrasses, shrubs, trees and flowers (Houdeshel and Pomeroy 2014).

To reduce nutrient leaching from growth medium, a sandy loam topsoil can be used. Many plants native to xeric climates are adapted to soils with high infiltration rates and low nutrient content (Houdeshel, Pomeroy and Hultine 2012).

Regarding maintenance, irrigation has been recommended during the first year of establishment for spring or summer plantings. Irrigation helps root systems develop so that they can access moisture deep in the growth medium. No irrigation should be required after establishment. Trimming bunchgrasses each winter promotes new shoot growth in the spring. Mulch, which requires upkeep and renewal, can be replaced by a layer of gravel to reduce maintenance needs. Light-colored gravel also decreases surface temperature and, therefore, plant water demand. Including a weed barrier below the gravel is recommended (Houdeshel, Pomeroy and Hultine 2012). The ability of properly selected native vegetation to survive a prolonged dry period without irrigation was demonstrated in a cold desert bioretention garden in Salt Lake City in which three different irrigation systems were compared for establishment. Almost all of the plants were growing well without supplemental irrigation two summers after establishment. The authors of the study suggest that based on regional hydrology, regionally native vegetation can be established without irrigation in bioretention gardens constructed in cold desert climates in any season other than the summer (Houdeshel and Pomeroy 2014).

For sizing, continuous modeling in addition to single storm event modeling should be used. Simulations using SWMM 5.0 were used to determine the garden to drainage area ratios for bioretention gardens in cold desert (Salt Lake City) and warm desert (Phoenix) sites. EISA[4] requires federal projects to manage the volume of rainfall from the 95th percentile storm, which requires the garden-to-drainage area ratio for Phoenix to be no more than 9:1 (Houdeshel, Pomeroy and Hultine 2012).

One suggested approach to siting bioretention cells is the use of high-resolution remote sensing data to extract land cover information (Khin et al. 2016).

4.2.6. Vegetative filter strips

In a few studies, vegetative filter strips have been assessed for their effectiveness in stormwater management under Mediterranean and seasonally dry conditions. Modeling and field study data have been used to assess control of fecal coliform bacterial loading, runoff reduction, pesticide loading reduction and soil loss from cultivated land and land used for livestock. Design criteria assessed included filter strip width as a function of soil type and topography, vegetation type and siting of BMPs.

4.2.6.1. Water quality improvement

The effectiveness of vegetative filter strips in reducing fecal coliform bacterial loads was assessed in a study of stormwater runoff from manure-fertilized dairy pastures in the Tomales Bay watershed, a region in California with a Mediterranean climate. In this observational, 1-year, longitudinal study, pastures varied in size and slope. The vegetation of the filter strips, primarily annual grasses with some associated forbs and perennial grasses, was dictated by the lifecycles of the plants and rainfall. Linear mixed effects regression was used to test for associations between management practices and $\log_{10}$ transformed fecal coliform bacterial concentrations. Directing runoff through the vegetative buffer was associated with a 24 percent reduction in concentration of bacteria per 10 m of buffer length (Lewis et al. 2010).

Researchers modeled the protection of receiving water bodies and aquatic organisms from pesticides in runoff by vegetative filter strips under the 30-year EPA scenario of dry Mediterranean, irrigated, intensive horticulture (California tomato). Vegetative filter length and application timing were found to be the most important input factors. The California tomato scenario was influenced primarily by irrigation events and therefore experienced a lower average cumulative runoff than under scenarios for other crops (Illinois corn and Oregon wheat) (Sabbagh, Munoz-Carpena and Fox 2013). In a follow-up modeling study of the efficacy of vegetative filter strips to limit pesticide transport from agricultural fields to receiving water using a framework that included degradation of pesticide trapped in a vegetative filter strip between runoff events, researchers investigated the California tomato scenario. The organic carbon sorption coefficient of the pesticide and the aerobic/anaerobic aquatic metabolism half-life were

[4] Energy Independence and Security Act of 2007, 42 U.S.C. § 17094 (2007).

the most important input parameters determining acute (peak) absolute and percent reduction in estimated environmental concentrations (Munoz-Carpena et al. 2015).

4.2.6.2. Stormwater management and soil erosion control

In a study combining field data from the Yakima River Basin in Washington State, a Mediterranean climate, with mechanistic modeling, the use of vegetative filter strips as BMPs to control sediment transport from furrow-irrigated agricultural land was assessed. Vegetative filter strips were installed at the end of furrows, and water runoff and soil loss to the irrigation return canal was modeled. The field experiments involved vegetative filter strip lengths ranging from 3.05 to 9.14 m. The researchers found that 5-m vegetative filter strips reduced water runoff and soil loss, on average, by 5 and 80 percent, respectively, but the BMP of less water-consumptive irrigation was more effective in mitigating both runoff and sediment delivery.

4.2.6.3. Design elements

A modeling study of BMPs for reducing soil erosion and sedimentation, a major problem in the seasonally dry Blue Nile Basin in Africa, using the Soil and Water Assessment Tool (commonly known as SWAT) showed that the effectiveness of filter strips depended on their width and the local topography (Betrie et al. 2011).

In a study by Campo-Bescós et al. (2015) using modeling and field data from furrow-irrigated agricultural land, the effectiveness of four types of vegetation were tested: Baronesse barley (*Hordeum vulgare*), alfalfa (*Medicago sativa*), Bromar mountain bromegrass (*Bromus marginatus*) and Rosana western wheatgrass (*Pascopyrum smithii*). Vegetation type did not affect runoff or soil loss reductions by vegetative filter strips, but the authors suggested that this insensitivity was caused by insufficient plant density to remove sediment. The optimal width of the vegetative filter strip depended on the soil type and local topography.

Siting of filter strips also can change effectiveness. A modeling study of a Mediterranean agricultural catchment (Roujan, southern France) showed that 70 percent of the variation of the net erosion was explained by variations in vegetative filter density. Although the density of the vegetative filters was the most sensitive parameter, strong interaction among the three modeling parameters (the density of vegetative filters, their downslope/upslope location probability, and the probability density function shape controller) when the density values are low indicated that their location may influence their global trapping efficiency in more realistic cases where few filters are in place (Gumiere et al. 2015).

4.2.7. Integrated systems

On a site scale, integrated systems have been studied for their efficiency in removing sediment, metals, trace organics, bacteria and nutrients under Mediterranean climate conditions. These studies have revealed some negative effects of integrated systems on effluent water quality. The effectiveness of integrated systems also has been assessed for stormwater retention. The systems contained combinations of detention basins, bioswales, bioretention cells and green street elements.

On a watershed scale, a modeling study has been conducted for a semi-arid region to optimize siting of LID BMPs to reduce nutrient and sediment loading.

4.2.7.1. Water quality improvement

The pollution removal efficacy of a bioretention system composed of four rain gardens and one bioswale was assessed in Daly City, California, a Mediterranean climate. The 427-m^2 system drained 16,200 m^2 of impervious area, and the bioretention cells were constructed of a layer of gravel mulch covering a layer of loamy sand mix above a pea gravel drainage gallery. The observed rainfall event that exceeded system capacity was 5 mm h^{-1}, which was consistent with permit requirements. Water samples were collected pre- and post-installation for a variety of storm events. The bioretention system reduced total suspended sediment loads in effluent from a mean of 21 mg L^{-1} before installation to 15 mg L^{-1} after installation. When the majority of the runoff was captured by the system, post-installation effluent concentrations for most trace metals (e.g., total and dissolved mercury, copper, zinc, nickel, lead, cadmium) were lower than before installation. Mean trace organic pollutant concentrations (i.e., total polychlorinated biphenyls, total PAHs and octachlorodibenzodioxin) also decreased after system installation. Effluent concentrations of metals were less variable after installation, indicating effective buffering by the bioretention system. Mean trace organic pollutant concentrations also decreased. The researchers concluded that pollutants such as metals and PAHs that originate from local sources and have high concentrations in runoff were removed effectively by the bioretention system (David et al. 2015).

Effectiveness at removing nutrients and sediment from urban runoff has been assessed for an integrated BMP system located in San Clemente Villages, California, and composed of a detention basin, a series of low-capacity vegetated swales, and a high-capacity vegetated swale. The 5.4 ha site treats runoff from recreational fields, parking lots and residential areas. Researchers found that the system reduced pollutant discharge through sedimentation, vegetative uptake and flow impoundment. The detention-based stormwater management system and low-capacity swales were effective at removing metals (i.e., cadmium, copper, lead and zinc) from the influent (Jiang, Yuan and Piza 2015).

In a green street project in Santa Monica, four types of BMPs were installed: subsurface plastic concave infiltration chambers under the parking lane; wider, depressed parkways with climate-appropriate flora and low-volume, solar-powered irrigation; gutter-oriented catch basin filters; and pervious concrete parking lanes. The system showed significant removal of heavy metals, mixed results for nutrients and reduced loadings for bacteria (Jiang, Yuan and Piza 2015).

4.2.7.2. Negative effects on effluent water quality

The bioretention system composed of four rain gardens and one bioswale in Daly City was found to be a source for methyl mercury. The researchers postulated that a design error might have resulted in anaerobic conditions at the bottom of one of the cells, creating conditions favoring mercury methylation by bacteria (David et al. 2015).

In the integrated BMP system in San Clemente Villages described by Jiang, Yuan and Piza (2015), the detention basin part of the system was effective in removing total nitrogen and orthophosphate, but the low- and high-capacity swales either had little effect on nutrient concentrations or acted as sources of nutrients.

Effluent from a green street project in Santa Monica had elevated TSS compared to the influent, likely because of runoff suspending particulates as it filtered through soils (Jiang, Yuan and Piza 2015).

4.2.7.3. Stormwater retention

Stormwater retention by a bioretention system has been assessed in the field under Mediterranean climate conditions. The demonstration bioretention system installed in Daly City was able to delay and reduce peak flow velocities and volumes. Because periods between storm events were brief during the two wet (winter) seasons monitored, the second of which was an abnormally high rainfall year, the soil and filter media stayed wet, resulting in only a small decrease of approximately 10 percent in flow volume compared with pre-installation flow. The authors indicated that longer periods between storms and maturing vegetation, which would produce more efficient evapotranspiration, would be likely to increase flow reduction (David et al. 2015).

4.2.7.4. Prioritization of siting

On a watershed scale, Martin-Mikle et al. (2015) developed an approach to identify priority sites for LID, using a large (666 km^2) mixed-use watershed in a semi-arid region of Oklahoma, the Lake Thunderbird Watershed, as a case study. More than 40 percent of the watershed is residential, with a high impervious surface coverage. Transport of phosphorus, nitrogen and sediment by urban runoff into the Lake Thunderbird Reservoir has led to exceedances of TMDL regulations. The researchers used geographic information system (commonly known as GIS) data on land cover, impervious surface, digital elevation model (DEM), soil conductivity, soil depth to restrictive layer, roads, zoning, building footprint, floodplain and waterbodies. They derived locations for implementing LID at local- (rain barrels, green roofs and porous pavement), intermediate- (rain gardens and bioswales), catchment- (detention and retention ponds) and reach-scale (riparian buffers) sites for hydrologically sensitive areas. Selected sites in subcatchments were validated by field visits, with a high rate of correctly identified sites (94%). In one subcatchment, results indicated an ability to reduce nutrient and sediment loading to receiving waters by 16 percent and 17 percent, respectively, by placing LID in 11 locations. On a watershed scale, hydrologically sensitive areas were concentrated in the western third of the watershed, an area of low infiltration capacity because of clayey soils and high rates of impervious cover because of development.

4.3. Stormwater management—watershed-scale research

On a watershed scale, green infrastructure approaches that can be used to manage stormwater include land conservation, preservation and restoration of riparian buffers, and enhancement of urban tree canopies. As for site-scale research, these practices have been evaluated for their ability to improve water quality, reduce erosion and reduce runoff. Best practices for restoration of degraded landscape-scale features have been studied. Siting of BMPs is an important design criterion. Irrigation is a primary maintenance consideration.

4.3.1. Land conservation

Prioritizing land conservation efforts has been an area of study. In addition, the likely effects of land conservation on stormwater management and use of conserved land in stormwater management have been modeled. Land conservation affects imperviousness, grass cover and—in the case of irrigated land—irrigation rates. Modeling studies have been undertaken in semi-arid and arid regions of the predicted effects of variables characterizing land use on the loading of nutrients, metals (e.g., selenium) and dissolved organic carbon (DOC) to receiving waters, as well as on total runoff and soil erosion.

4.3.1.1. Prioritization of siting

Prioritizing sites for land conservation is an active area of research. A landscape-scale geospatial assessment of wetlands was conducted in Wyoming, quantifying the wetlands' biological diversity, protection status, susceptibility to climate change and proximity to sources of impairment. The researchers determined that low-elevation wetland complexes were the least protected, in the poorest current condition, and the most vulnerable to future land-use changes (Copeland et al. 2010). In a study conducted in coastal California that focused on Sonoma County (Mediterranean climate), 564 km^2 were identified as being both flood-prone and of natural resource conservation value. The authors suggest using flood mitigation grant programs as a source of funds for property/structure buyout and habitat restoration projects (Calil et al. 2015).

4.3.1.2. Water quality improvement

The predicted effects of conservation of agricultural lands on water quality have been modeled. Transport and chemical reaction processes were modeled for Colorado's Lower Arkansas River and its tributaries (Köppen climate classification BSk: cold, arid steppe). In the study by Bailey, Gates and Romero (2015), fallowing cultivated land to allow irrigation water to be leased to municipalities was predicted to have a strong positive effect on nitrate loading to ground water. Intermittent fallowing of 25 percent of the land resulted in a forecasted decrease of about 15 percent in nitrate ground water loading to streams (Bailey, Gates and Romero 2015). The same watershed was modeled for the effects of BMPs on selenium loading. Land fallowing, as well as the other water management BMPs modeled (i.e., reduced irrigation and irrigation canal sealing) were predicted to yield an immediate, significant effect on selenium mass loading to the Arkansas River and a significant decrease in mass loading during the 38-year period modeled, much more than the land-management BMPs (Bailey, Romero and Gates 2015).

A modeling study was conducted of the effects of the changes in infrastructure design that occurred from 1955 to 2010 (i.e., a shift from pipes to engineered channels and retention basins to natural washes) in an arid city (the greater Phoenix area). Stormwater runoff was monitored at outlets from nested watersheds, measuring discharge, dissolved nitrogen, dissolved phosphorus, DOC and rainfall (where not already monitored). Path analysis was used to test hypotheses about the relationships among infrastructure characteristics, energy use by buildings for heating and cooling, land cover, storm characteristics, and nutrient (dissolved nitrogen and phosphorus) and DOC delivery to the watershed. Imperviousness and grass cover were the most important land-cover variables for predicting nutrient and DOC loading. Nutrient and DOC concentrations, however, were most strongly related to antecedent and storm characteristics (Hale et al. 2015).

The adoption of water-sensitive urban design in established urban areas by using a portion of the land in existing parks for stormwater filtration was explored in a region of South Australia with a

Mediterranean climate. The results of the modeling study showed that allocating 10 percent of parks that cover less than 16 percent of the landscape for bioretention devices would result in a 62 percent reduction of nitrogen from stormwater (Segaran, Lewis and Ostendorf 2014).

4.3.1.3. Soil conservation

The potential benefits of land conservation for the prevention of soil erosion were compared to those from landscape design in a watershed with a Mediterranean climate (Languedoc-Roussillon, France). The researchers found that land use was the major factor controlling sediment production (David et al. 2014). In a study of a Mediterranean region in southeast Spain, land management (i.e., seasonal set-aside land management) and land uses (i.e., urban, agricultural, scrubland, forest and dense forest) were found to be most important in affecting erosion and sediment yield (Rodriguez-Lloveras et al. 2015).

4.3.1.4. Stormwater retention

In the modeling study by Hale et al. (2015) of watersheds in Phoenix, effects of different parameters on runoff reduction were assessed in addition to effects on water quality. Imperviousness and grass cover were found to be the most important land-cover variables for predicting runoff reduction, being more significantly correlated with runoff than connected imperviousness or soil cover.

4.3.1.5. Reestablishment of vegetation

Reestablishment of native vegetation was studied on abandoned drill pads and infrastructure in southwestern Wyoming, a cold, arid environment. Soil moisture retention was improved using hollow frame snow fencing, a technology engineered to alter the snowpack without the negative effects of traditional snow fencing on sagebrush dominance. Snow fencing significantly increased the establishment of native sagebrush-steppe species, with fewer invasive species than control areas (David 2013).

4.3.2. Riparian buffers

Riparian buffers have been studied for their ability to improve water quality in semi-arid conditions. Modeling studies have examined the predicted effects of enhanced riparian buffers on nutrient and selenium loading. The effects of buffer width on river habitat for fish also have been studied in dry forests. Human and natural factors affecting riparian ecosystems, as well as practices for restoring native vegetation, also have been studied under semi-arid conditions.

4.3.2.1. Water quality improvement

In a modeling study comparing different BMPs in Colorado’s Lower Arkansas River and its tributaries, a combination of reducing fertilizer application, reducing irrigation, sealing irrigation canals and enhancing riparian buffer zones was predicted to have the greatest overall impact on regional nitrate concentrations in ground water and mass loading to the river network compared to other BMP combinations (Bailey, Gates and Romero 2015). In a separate study, enhanced riparian buffers was one of the BMPs modeled in the Lower Arkansas River Valley in southeastern Colorado to identify practices for mediating selenium toxicity in surface water. Selenium, which is toxic at high concentrations, is a problem in many river basins in the western United States, where selenium-bearing shales oxidized by oxygen and nitrate represent a source of the metal. Enhancement of riparian buffers was one of the most effective practices modeled, resulting in a 14 percent selenium load reduction when combined with reduced irrigation (Bailey, Romero and Gates 2015). A field study comparing nutrient uptake and immobilization by riparian plant communities in the Sacramento Valley, California, revealed that riparian zones with woody plant communities had lower soil nitrate and plant-available phosphorus levels. Lower soil nutrient loading also was correlated with higher visual riparian health assessment scores, a quantification of channel condition, access to the floodplain, bank stability, extent of natural riparian zone vegetation, macroinvertebrate habitat, pool variability and pool substrate (Young-Mathews et al. 2010).

4.3.2.2. Habitat preservation performance

Large woody debris and stream water temperature are important factors in providing fish habitat in rivers. A modeling study that included dry, Douglas fir (*Pseudotsuga menziesii*) forest types in southwest, central and north Idaho found that timber harvesting could be compatible with maintaining habitat objectives for large woody debris and stream shade if only light thinning was allowed in an inner 25-foot buffer zone with heavier thinning in the outer 50-foot zone (Teply, McGreer and Ceder 2014).

4.3.2.3. Reestablishment

Restoration of riparian buffer zones may involve removal of invasive species and planting of native species. Researchers have studied the best conditions for reestablishing willow in riparian buffer zones. A study compared aerial cover, height and stem density attained by dormant coyote willow (*Salix exigua*) cuttings planted along the banks of the Middle Rio Grande in central New Mexico (semi-arid). Regression analysis of the percent of fine-textured soil material and available water at different depth increments at planting sites revealed that cuttings attained growth comparable to natural willow stands if the floodplain soil contained intermediate levels of fine-textured soil material, and the maximum depth to ground water was within 1.5 m of the ground surface. Where sites are dominated by coarse sand, growth was improved if the ground water was within 1 m of the surface (Caplan et al. 2013). Although the dominance of non-native species has significant ecological effects, a recent review concluded that the dominance of non-native species is unlikely to significantly affect streamflow volume or ground water levels (Hultine and Bush 2011).

Riparian restoration also can involve such practices as intentional water releases from dams, effluent subsidies, water conservation measures and removal of artificial bank protection (riprap). In a study of the Sacramento River, human pressures over time (1942–1999) were shown to increase bank erosion, increase channel length and decrease active channel width. How to reverse these changes is difficult to predict because of the various human (e.g., bank protection, flow diversion, sediment starvation and land-use changes) and natural changes (i.e., flood sequences acting throughout the period and the geological setting) acting over different time scales. The authors highlight the important effects of the Shasta Dam, which reduced peak flow and bedload sediment supply on channel conditions. They also note, however, the effects on the river banks, river channel and floodplain lakes of bank protection and the construction of flood control structures; land-use changes (especially conversion of riparian forest to agriculture); changes in tributary sediment delivery; local geologic controls; and the sequence of large floods (Michalkova et al. 2011).

The use of effluent subsidies from the Nogales International Wastewater Treatment Plant on riparian vegetation development and distribution in the Santa Cruz River Valley was investigated. The current amount, distribution and diversity of vegetation was found to be linked to effluent supply, but an initial rapid increase in the area of riparian forest and woodland after receiving effluent was followed by extensive cottonwood tree die-off. The sites that did not receive effluent were dominated by riparian shrub and non-native herbaceous vegetation but were more diverse and stable over time, indicating variable long-term effects of riparian restoration by effluent subsidy that depended on land-use history (Villarreal et al. 2012).

The effects of anthropogenic water withdrawal on pioneer riparian forests have been studied on the Upper San Pedro River in semi-arid Arizona. Native *Populus-Salix* forests increased most in conservation areas with perennial stream flows, whereas deeply rooted, invasive *Tamarix* dominated in agricultural areas, which were drier (Stromberg et al. 2010). The types of plant communities that are established naturally in arid alluvial fan and fluvial dry wash surfaces were found to depend on whether the surfaces were dominated by high-energy flash floods or lower energy sedimentation processes (Dickerson, Forman and Liu 2013). In a study of an ecological water diversion project in the lower Tarim River, which flows through a semi-arid region in China, ecosystem restoration was observed to be in progress, but restoration of dense vegetation in the riparian buffer needed continuous water diversion (Sun et al. 2011).

4.3.3. Urban tree canopies

The effects of urban trees on stormwater conservation and infiltration—as well as estimates of tree canopies' irrigation needs—have been the subject of field and modeling studies under semi-arid and Mediterranean climate conditions. The effects of turfgrass shading, tree species selection and tree density on irrigation needs were assessed. In addition, tree canopy traits were investigated for their effect on the funneling of precipitation from canopy to ground.

4.3.3.1. Stormwater infiltration

The effects of different canopy traits on metrics of stemflow, the portion of precipitation incident on vegetation canopies that is funneled to the base of the plant rather than reaching ground directly from gaps in the canopy or evaporating from leaf and wood surfaces, were studied in deciduous trees in a semi-arid climate (Kamloops, British Columbia, Canada). Stemflow production was positively correlated with high branch angles, low bark relief in multi-leader trees and high bark relief for single-leader trees, and greater rain event depth. For rain depths less than 3 mm, greater stemflow was associated with leafless canopies (Carlyle-Moses and Schooling 2015). In another study at the same location, Schooling and Carlyle-Moses (2015) found individual tree stemflow percentages (i.e., stemflow volume as a percentage of rain incident on the canopy) were variable even for similar rain depths, which the authors suggested was a result of meteorological factors. The maximum stemflow was 22.8 percent for a columnar English oak. The results of the study indicate that site-scale water balances may be affected greatly by isolated deciduous trees with traits conducive to stemflow production, making the infiltration capacity at the bases of urban trees important for the design of stormwater management with vegetation.

4.3.3.2. Stormwater conservation

Modeling residential irrigation water demand over time in Salt Lake City, researchers determined that as urban tree canopy increases in residential urban areas, exposed turf grass decreases. As a result, a slight decrease in residential landscape water demand was predicted because of variations in evapotranspiration rate with landscape type (Lowry, Ramsey and Kjelgren 2011). A field study comparing evapotranspiration rates of unshaded urban lawns with urban lawns composed of trees and turfgrass groundcover in Los Angeles showed that irrigated turfgrass evaporation always was higher than plot-scale tree transpiration by up to a factor of 10. The reduction in evapotranspiration of turfgrass was attributed to shading effects of trees, which were more important than increased transpiration from trees. Partially shading irrigated lawns with trees is therefore a potential water-saving measure in seasonally dry climates (Litvak, Bijoor and Pataki 2014).

4.3.3.3. Irrigation needs

A field study of urban tree transpiration rates in Los Angeles found very large species differences in whole-tree transpiration rates, and measured results did not necessarily support common assumptions about high versus low-water-use trees (e.g., species native to Mediterranean climates have low rates of water use) or reflect transpiration rates in natural ecosystems. Plot-level transpiration rates for single species were estimated to increase with tree density, although the model did not consider such nonlinear feedbacks to transpiration at high canopy density as self-shading, altered tree shapes and reduced canopy-atmosphere coupling. One million new trees, a proposed target for a large-scale tree planting in Los Angeles, would use approximately 5 percent of the total daily municipal water use if high-water-use species were planted (Pataki et al. 2011).

4.4. Stormwater conservation

For stormwater conservation, two primary practices are described: water harvesting for agricultural production and roof-top water harvesting systems for nonpotable use, including indoor use and landscape irrigation. The effectiveness of different types of rainwater harvesting systems have been compared for their ability to support vegetation, reduce soil erosion, and meet nonpotable and domestic water needs. The impact of rainwater harvesting on the water balance of a watershed has been assessed. Design elements to maximize effectiveness of practices also have been studied.

4.4.1. Agricultural rainwater harvesting

The effectiveness of rainwater harvesting technologies in dryland agriculture for decreasing runoff, increasing infiltration rates, increasing crop yields and conserving soil has been assessed under semi-arid conditions in Africa, Asia and the Middle East. The ability of rainwater harvesting to decrease surface runoff, increase infiltration, reduce soil erosion and decrease soil bulk density has been measured in the field. In addition, the effects of different techniques of rainwater harvesting on crop yield and forage biomass have been assessed, and for some techniques, the efficacy of different designs has been evaluated. Possible negative effects of rainwater harvesting on downstream surface water flow also have been modeled.

4.4.1.1. Water harvesting effectiveness for infiltration

Green infrastructure techniques have been shown to be effective in water harvesting for agriculture in semi-arid regions. In mountainous, semi-arid regions of the Kingdom of Saudi Arabia, farmers traditionally grew crops by constructing soil and stone terraces within juniper forest and woodlots. In recent times, many of these terraces were abandoned or damaged. In a study comparing plots containing abandoned or maintained terraces, maintaining terraces was found to decrease surface runoff and increase infiltration rates (El Atta and Aref 2010).

4.4.1.2. Effect on crop yield and forage biomass

A literature search was conducted by Bouma, Hegde and Lasage (2016) to identify studies in semi-arid regions of Africa and Asia for a meta-analysis of the effectiveness of rainwater harvesting techniques that collect, store or conserve water (as opposed to interventions that increase the capacity of soil to retain water, such as conservation agriculture). Included studies were published from 1989 through 2011. The authors distinguished between soil storage technologies (e.g., planting pits, earthen bunds, plastic-covered ridge-and-furrow, stone bunds, terraces) and reservoir storage technologies (e.g., household ponds, small check dames, underground water tanks). Rainfall data were included in the database to distinguish possible effects from optimal rainfall years. Mann-Whitney significance tests were conducted to assess whether water harvesting technologies' effects on crop yields were significant and whether crop yield effects differed across rainfall classes. An econometric analysis was conducted to assess the effects of other factors (e.g., rainfall, soil fertility treatment) on crop yield improvements. For the crop with the largest number of observations, maize (n = 90), plot- and farmer-associated characteristics were captured by including information about initial crop yields. Of the 158 peer-reviewed studies that reported the impacts of water harvesting technologies, 29 studies reported crop yield changes. Seventeen of the studies that reported crop yield changes reported relative yield change excluding soil fertility treatment, and 15 of them studied maize yield change. Although the average yield change was large (78%), the standard deviation and range were substantial. Excluding soil fertility treatment did not affect the results significantly. Absolute rainfall did not significantly affect the changes in yield for either in-soil or reservoir water harvesting. Rainfall harvesting appeared to be especially effective in low-rainfall conditions (below 330 mm). Studies in which yields were high showed less relative crop yield improvement from water harvesting technologies. No significant difference was observed between in-soil and reservoir water harvesting technologies.

A more recent study examined the efficacy of in-field rainwater harvesting on crop yield compared to conventional tillage. In a rural, semi-arid region of South Africa, in-field rainwater harvesting was found to increase maize yields slightly compared with conventional tillage (Botha, Anderson and Van Staden 2015).

4.4.1.3. Soil conservation

In their study of terraces constructed in juniper forests in Saudi Arabia, El Atta and Aref (2010) found that abandoning rainwater-harvesting terraces increased soil loss and soil bulk density.

4.4.1.4. Water consumption by rainwater harvesting

The downstream effects of improving soil water availability through rainwater harvesting were modeled in a semi-arid area of Iran. Reductions in the mean annual and mean monthly flows were modest, ranging from 2 to 5 percent and 1 to 9 percent, respectively, and much less than converting rain-fed areas to irrigation agriculture (Masih et al. 2011).

4.4.1.5. Design elements

Innovations in plowing techniques for water harvesting have been investigated. In an arid environment (Muwaqqar, Jordan), a new water harvesting microcatchment technique, wide furrow with back-placed transplanting area, was tested. The technique, which uses a new type of inexpensive plow, was compared to deep furrow plowing. The deep furrow technique showed higher water-harvesting efficiency and greater soil water storage, but both techniques had comparable plant productivity. The wide furrow with back-placed transplanting area technique is uniquely amenable to mechanized planting and maintenance, however, which would encourage large-scale implementation (Gammoh 2013). The ridge-and-furrow system was found to increase soil water content, soil water storage at 30 cm depth, soil surface temperature and yields of Siberian wildrye (*Elymus sibiricus*) in a semi-arid region of North China (He et al. 2012). A study was conducted optimizing ridge-and-furrow ratios and ridge mulching materials for the growth of alfalfa (*Medicago sativa* L.) in a semi-arid region of Northwest China. The authors found that ridge mulching materials and ridge widths had distinct effects on topsoil temperature at ridge tops but not at furrow bottoms. Higher than average rainfall led to significant decreases of forage yields for manually compacted ridge soil and significant increases of forage yields for biodegradable mulch film and common plastic film (Wang et al. 2015).

Different mulching techniques have been compared for their effectiveness. A study conducted in the semi-arid lands of China's Loess Plateau found that plastic-covered ridge and furrow rainwater harvesting and furrow-applied mulching performed better than bare furrow treatment in increasing the yield of corn. The plastic mulch performed best in water use efficiency compared with a liquid film or a biodegradable film. Corn stover mulch performed worse than bare farrow (Chen et al. 2013). Another study of mulches using the ridge-and-furrow rainfall harvesting system in the Loess Plateau compared standard plastic film, biodegradable film, maize straw and liquid film to a conventional flat, no-mulch control. Standard plastic film, biodegradable film and maize straw significantly increased maize yields by 35, 35 and 34 percent, respectively (Li et al. 2012). A comparison of surface treatment techniques (i.e., natural, plastic cover, stone cover, hay cover and compaction) in an arid environment in Turkey found greatest water harvesting efficiency with plastic cover, but runoff improvements were lost when soil was saturated with water. Average pistachio plant heights were highest with plastic cover, followed by surface compaction, hay cover and stone cover. The authors noted potential environmental problems, however, with plastic cover (Yazar et al. 2014).

Traditional and new rainwater harvesting techniques have been compared in the field under semi-arid conditions. In a semi-arid region of Zimbabwe, researchers compared soil moisture and crop yield with dead-level contoured plots, noncontoured plots and plots with traditional graded contours. They found that dead-level contours resulted in crop yield benefits in fields with soil type conditions that enable runoff generation (silt loam soil) but were not likely to have benefits in soils with low runoff generation (sandy soil) (Mhizha and Ndiritu 2013). In a study in Jordan of arid rangeland, the effects of three water harvesting techniques—contour furrows and crescent-shaped and v-shaped microcatchments—were studied on biomass production and natural vegetation. The researchers found that using contour furrows gave higher shrub biomass when compared to the crescent- and v-shaped techniques (Saoub et al. 2011). Modifying contour ridges traditionally used for rainwater management by digging infiltration pits inside contour ridge channels was found not to improve maize yield or soil moisture content in a study in semi-arid Zimbabwe (Nyakudya, Stroosnijder and Nyagumbo 2014).

In addition, an integrated system of micro-flood irrigation and in-field rainwater harvesting with alternating basin and runoff strips was optimized in a semi-arid region of the Free State Province (South Africa). Different strip widths were tested. For a 1-m runoff strip width, crop biomass and grain yield were 19 percent and 32 percent above average. The 1-m runoff strip and full irrigation produced optimum yields (Mavimbela and van Rensburg 2012).

4.4.2. Rain barrels and cisterns

Modeling studies have been conducted under Mediterranean, semi-arid and arid climate conditions to assess the effectiveness of rainwater harvesting with rain barrels and cisterns to meet nonpotable water demand and contribute to stormwater management. The effects of storage capacity, local precipitation data and downspout disconnection have been considered. Design criteria including slope, roughness and tank sizing have been evaluated in Mediterranean and arid regions.

4.4.2.1. Conservation effectiveness

A water-balance analysis using EPA's SWMM model was conducted to determine the water supply benefits of rainwater harvesting in U.S. cities, including two in the semi-arid Mountain West (Denver and Salt Lake City), three in the arid Southwest (Albuquerque; Phoenix; and Las Vegas, Nevada) and three from semi-arid and Mediterranean climates on the West Coast (Sacramento, San Diego and Los Angeles), using precipitation and water demand data from the modeled cities. They found a wide variation in cistern size needed to achieve 80 percent rooftop runoff capture (i.e., 757 liters for the Southwest, 946 liters for the Mountain West and 3,028 liters for the West Coast). The drier regions (Mountain West and Southwest) required smaller cisterns for 80 percent capture but were able to supply only a fraction of their indoor water needs (i.e., 47% and 19%, respectively). Installing a single rain barrel (150 liters) would represent less than a 30 percent nonpotable indoor water-saving efficiency for the West Coast, Mountain West and Southwest regions (Steffen et al. 2013).

A modeling study including cities located in both Mediterranean and arid climates in Iran determined that residential rainwater harvesting could supply 75 percent of nonpotable water demand in buildings with larger roof areas 40 percent of the time. In arid climates, rainwater harvesting was predicted to be able to meet 75 percent of nonpotable water demand only 23 percent of the time (Mehrabadi, Saghafian and Fashi 2013).

A water balance model compared potential water supply savings from rainwater collected from residential roofs and gray water generated by domestic use in a Mediterranean climate (Cranbrook, Western Australia). Historical daily rainfall and evaporation data from 1950 to 2006 were used in the model. The researchers found that gray water use had a greater maximum reduction of nonpotable indoor and irrigation demand (32.5%) than rainwater harvesting (25.1%) (Zhang et al. 2010).

4.4.2.2. Stormwater management

The ability of rainwater harvesting to reduce runoff has been modeled at the neighborhood and watershed scales under arid, semi-arid and Mediterranean climate conditions. In an analysis by Steffen et al. (2013), the performance of rainwater harvesting was modeled using a Salt Lake City neighborhood as a case study with precipitation data from cities in the Mountain West (Salt Lake City), the Southwest (Phoenix) and the West Coast (Sacramento). Rainwater harvesting was predicted to reduce runoff volume up to 20 percent in semi-arid regions. In a watershed-scale simulation of the Chollas Creek watershed in San Diego (Mediterranean climate), runoff reductions increased linearly with storage capacity and the number of implementing households. Maximum reduction ranged between 10.1 and 12.4 percent using precipitation data from 1948 to 2011. Sensitivity analyses found that long-term watershed runoff reduction potential was affected primarily by precipitation characteristics and disconnection of rooftop runoff rather than available cistern capacity (Walsh, Pomeroy and Burian 2014).

In the study by Zhang et al. (2010) comparing residential rainwater harvesting and gray water reuse in West Australia, gray water harvesting reduced stormwater runoff by 54.1 percent or 88.1 m^3/lot/year, and rainwater harvesting reduced stormwater runoff by 48.1 percent or 68.3 m^3/lot/year.

4.4.2.3. Cost-benefit analysis

The costs and benefits of office building rainwater harvesting systems were assessed in different locations, including cities located in arid, semi-arid and Mediterranean climates (Albuquerque; Phoenix; Salt Lake City; San Diego; and San Francisco, California). The water-saving efficiency (i.e., average percent of water demand substituted by rainwater yield) plateaued at lower values for these cities located in dry climates compared to temperate cities (Atlanta, Georgia; Boston, Massachusetts; Dallas, Texas; New York, New York; Philadelphia, Pennsylvania; Seattle, Washington; Tampa, Florida; and Wichita, Kansas), although runoff volume reduction potentials (i.e., average percent of rooftop runoff captured relative to that generated) were higher for cities in dry climates (see Figure 4-1). The authors suggest that considerations of the costs (including local water utility rates) and benefits of systems should include both direct benefits such as stormwater management and indirect benefits such as CSO mitigation (Wang and Zimmerman 2015).

4.4.2.4. Design elements

Criteria for roof design to maximize rainwater quantity and quality were developed in a study in Barcelona, Spain (Mediterranean climate). The researchers found that sloping, smooth roofs may harvest as much as 50 percent more rainwater than flat, rough roofs. In general, physicochemical runoff quality was better than the average quality as described in the literature, but sloping roofs had significantly better results for some water quality parameters than flat, rough roofs (Farreny et al. 2011).

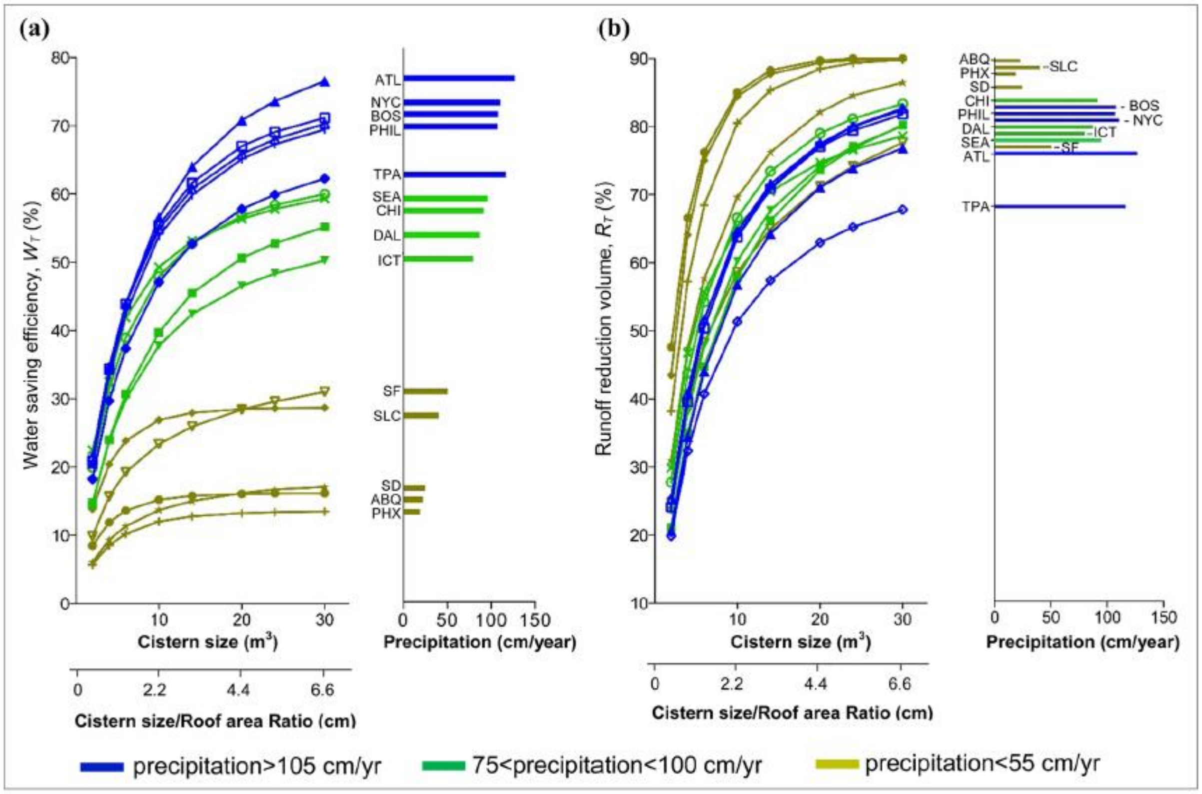

Figure 4-1. Comparison of water saving efficiency and runoff volume reduction for U.S. cities by annual precipitation levels.

(a) Average water saving efficiency (W_T), (b) average runoff volume reduction (R_T), and (c) regression analysis results with respect to different cistern sizes for 14 U.S. cities. Abbreviations of western and southwestern cities: ABQ = Albuquerque, PHX = Phoenix, SD = San Diego, SF = San Francisco, and SLC = Salt Lake City. The remaining cities are Atlanta, Boston, Dallas, New York City, Philadelphia, Seattle, Tampa and Wichita.

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Sizing for reliability, particularly for indoor water use, is another design criteria. The performance of different size systems in arid Australia has been evaluated. The reliability of a rainwater harvesting system was highly dependent on mean annual rainfall. A 20-kL tank was predicted to provide a reliability of 61 to 97 percent for toilet and laundry use of a household in arid Australia (Hajani and Rahman 2014). A study in semi-arid Texas used a nonparametric stochastic rainfall generator and 64 years of rainfall data to provide engineering charts and equations to estimate system requirements of roof capture area and cistern capacity to meet 100 percent of the domestic water requirements for households with varying numbers of occupants. All systems models were able to meet all requirements for a one-occupant household, at least a 3,500 square foot roof was required (with 40,000 gallon cistern) for a two-occupant household, and no combination of roof and cistern size was able to meet all requirements for a three-occupant household (Fulton et al. 2013).

An environmental analysis of rainwater harvesting systems for urban areas in Mediterranean climates quantified the environmental impacts of systems through a life cycle assessment (i.e., materials, construction, transportation, use and deconstruction). The researchers found that a distributed-over-roof tank had the least negative environmental impact compared to the other storage systems modeled (i.e., an underground tank and a tank below the roof) because of better distribution of tank weight on the building, reduced reinforcement requirements and enabled energy savings. The storage subsystem and the materials stage contributed most significantly to the impacts. The most efficient system was a building-scale system in a compact neighborhood with a tank distributed over the roof. It was comparable in global warming potential (measured in production of carbon dioxide equivalents) to water production and distribution by the existing drinking main water supply and had no energy demand during use (Angrill et al. 2012).

Chapter 5.

Proposed Areas of Research for EPA

In this chapter, research topics of interest to EPA on applying green infrastructure in arid and semi-arid climates to manage and conserve stormwater are presented. Research topics were identified by experts participating in a March 2012 workshop on creating a research agenda on adapting green infrastructure to arid environments. Additional suggestions for further study were drawn from the literature surveyed in Chapter 4. These suggestions are grouped by BMP, just as the research results were organized in Chapter 4. Finally, a summary of research themes that are general to multiple practices is included in this chapter.

5.1. AridLID 2012 research agenda

In March 2012, the third Arid Low Impact Development (AridLID) Conference was held in Tucson, Arizona. The 2012 AridLID Conference featured a workshop titled "Co-Creating an Arid-Adapted, Integrative Green Infrastructure Research Agenda." The report from the workshop formulates and prioritizes research questions regarding arid green infrastructure and LID and recommends particular research questions relevant to EPA's mission that might be addressed by the Agency in collaboration with nonfederal and federal agency partners (Cleveland 2013).

5.1.1. EPA and nonfederal stakeholders

The workshop participants identified research questions for EPA to address in collaboration with nonfederal stakeholders:

- Pretreatment and treatment needs before infiltration.
- Review of institutions, codes and ordinances for treating soil as a resource.

To better understand pretreatment and treatment needs before infiltration, research should determine watershed characteristics and constituents of runoff; study the kind of treatment that is accomplished by native soil; and determine the life-cycle costs of maintenance, particularly those associated with clogging. Determining the levels of metals, nutrients and sediment in stormwater and their impact on ground water quality is needed. Possible partners include university researchers, geotechnical engineers and science-based nongovernmental organizations.

Also needed is a comprehensive review of institutions, codes and ordinances for treating soil as a resource. Municipalities and other MS4 permit-granting jurisdictions, as well as members of the public, can assist EPA in developing this resource. Possible approaches include studying open space, documenting remediation and soil restoration regulations, defining soil resource areas, and researching soil transport needs.

5.1.2. *Cross-federal agency research*

Additional research opportunities would best be addressed if EPA were to partner with other federal agencies. The opportunities include the following:

- Plant/soil interactions and pollutant removal.
- Impact of green infrastructure/LID on flood frequency and volume.
- Impact of green infrastructure/LID on floods as a downstream resource.
- Ground water impacts resulting from water infiltration.
- Database of existing findings.
- Process for prioritizing projects within a watershed.

Potential federal partners with EPA to study plant/soil interactions and pollutant removal include the U.S. Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) and the U.S. Geological Survey (USGS). The NRCS conducts the National Cooperative Soil Survey, data from which is available online (NRCS 2013), and operates the Tucson Plant Materials Center, which produces nursery stock and seeds for regional projects. The USGS produces geochemical and mineralogical soil maps for soils in the conterminous United States (Smith et al. 2014). Other potential partners include academia, state-level environmental protection agencies, consultants and private industry. The study of plant/soil interactions and pollutant removal can best be approached by developing small-scale models, undertaking pilot comparative projects across the region, using lysimeters to create an evapotranspiration database, conducting short- and long-term studies, comparing soil and vegetation maps, studying sunlight impacts, and studying impacts at different depths.

Assessment of the impact of green infrastructure/LID on flood frequency and volume, as well as water as a downstream resource, can be accomplished through collaborations between EPA and flood control districts, academia, the U.S. Department of Housing and Urban Development, the Bureau of Reclamation, the U.S. Army Corps of Engineers, the USGS, and professional associations. Possible approaches include modeling LID practices and runoff reduction, determining maintenance requirements and long-term costs, conducting monitoring efforts to capture data from established testing and control sites (or before-and-after studies), and assessing impacts on downstream vegetation and riparian habitat.

Impacts on the quantity and quality of ground water impacts resulting from stormwater infiltration merit further study. Potential research partners with EPA include the U.S. Department of the Interior's Bureau of Reclamation, state-level environmental protection agencies, the USGS, USDA's Agricultural Research Service, water utilities and nongovernmental organizations. Research approaches include studying tracers in stormwater; conducting bench-scale tests of absorption rates of various pollutants; sampling at different locations in watersheds; assessing the long-term viability of reclaim systems to recharge; modeling infiltration; and conducting a comparative analysis among natural, concretized, bank-protected and sandy-bottom washes.

Compiling a database of existing findings, providing a process for prioritizing projects, and identifying prioritization criteria are important research goals. Research partners with EPA could include the Agricultural Research Service, academia and student organizations. Potential products from this research could include technical manuals describing BMPs, an international BMP database, a compilation of local knowledge of BMP effectiveness and documentation of vegetation types and functions.

5.2. Stormwater management research needs—site scale

Experts in the field have identified research needs for applying site-scale green infrastructure to stormwater management in arid and semi-arid regions. Their recommendations include replicating field studies; investigating the mechanisms behind effects on stormwater quality; optimizing design criteria; exploring sustainable solutions to irrigation needs; improving models of effectiveness by refining model parameters, validating models with field studies, conducting sensitivity and uncertainty analyses, and incorporating high-resolution data; developing a better understanding of maintenance needs; and optimizing siting of BMPs.

5.2.1. Bioswales

In a study conducted by Dorsey (2010), a wetland swale showed promise in reducing bacterial loads to beaches in a trial under Mediterranean climate conditions. The author suggests conducting similar projects to assess bioswales for fecal indicator bacterial removal to better judge their success at filtering runoff and reducing bacterial densities along beaches.

5.2.2. Green roofs

Key areas for research on the implementation of green roofs in arid and semi-arid environments include better understanding the potential negative effects on effluent water quality, improving planting strategies, increasing water retention, selecting substrates and applying irrigation.

5.2.2.1. Negative effects on effluent water quality

Short-term studies have shown that green roofs can act as pollutant sources. Researchers recommend a long-term study of their effects on water quality in arid and semi-arid climates (Beecham and Razzaghmanesh 2015).

5.2.2.2. Planting strategies

Authors of studies of green roofs in dry climates had the following recommendations for future study of planting strategies:

- Research must focus on which plants provide desired characteristics to green roofs (e.g., stormwater retention, building cooling) rather than which simply survive (Simmons 2015).
- It is necessary to identify plants that can adapt to a broad range of conditions because global climate change is predicted to increase climate variability (Simmons 2015).

- Performance differences between monoculture and heterogeneous plantings should be assessed (Razzaghmanesh, Beecham and Brien 2014).
- A better understanding of how to select appropriate drought-tolerant plant species is needed (Van Mechelen, Dutoit and Hermy 2015).

5.2.2.3. Water retention

The following topics regarding water retention by green roofs in arid and semi-arid environments were recommended for further study:

- The effects of antecedent dry weather periods and evapotranspiration on water retention by green roofs in dry climates (Beecham and Razzaghmanesh 2015).
- The effectiveness of water-retention additives for green roof design in dry climates because of their species-specific effects on drought resistance (Farrell, Ang and Rayner 2013).
- Long-term effects of hydrogels on plant water status (Savi et al. 2014).
- Substrates with greater water-retaining capacity (Van Mechelen, Dutoit and Hermy 2015).

5.2.2.4. Substrates

Because of the vulnerability of root systems to high temperatures, more research is needed on the thermal properties of growing media for extensive green roofs in hot climates. Additional research also is needed on the optimal water retention and drainage characteristics for growth media in arid and semi-arid climates (Simmons 2015).

Interactions between different polymer hydrogels and substrates also should be studied, particularly over the long term (Savi et al. 2014).

5.2.2.5. Irrigation

Further investigation is needed on the optimal irrigation regimes for green roofs in arid and semi-arid environments (Van Mechelen, Dutoit and Hermy 2015).

5.2.3. Permeable pavement

Further research on the accuracy of paved area reduction factors is needed by comparing larger watersheds with various imperviousness and overland routing percentages. TMDLs also could be compared to an incentive index developed for the volume-based paved area reduction factors (Blackler and Guo 2014).

Modeling results alone should not be relied on for designing permeable shoulder pavement. Pilot investigations using heavy vehicle simulators to verify the design depth and structural integrity of pavement under realistic load and traffic conditions should be conducted (Chai et al. 2012).

Because soil clogging can reduce the freeze-thaw durability of pervious concrete, the efficacy of maintenance procedures for cleaning partially clogged pervious concrete slabs should be investigated in future research (Guthrie, DeMille and Eggett 2010).

5.2.4. Planter boxes

Pilot experiments showed that a bioretention environment is favorable for the growth of common roadside weeds in Texas, but further study is needed to determine whether similar successional changes from planted vegetation to the predominance of weeds will occur under field conditions (Li et al. 2011).

More studies are needed to delineate the rooting effects of different vegetation on performance of bioretention units, because rooting has been shown to affect retention times and pollutant removal efficiencies (Kim et al. 2012)

5.2.5. Rain gardens/bioretention cells

Additional study is needed on nutrient retention, leaching of metals into effluent, irrigation needs, siting optimization using remote sensing, and optimal design criteria for arid and semi-arid climates. Nutrient retention is a particular concern, and research is needed under different time scales and water availability conditions. Possible design elements that merit further research include improved root accessibility to deeper water sources, media type, vegetation density and sizing appropriate to evaporation and transpiration rates characteristic of arid and semi-arid climates.

5.2.5.1. Nutrient retention

Studies are needed of the carbon budgets of bioretention systems in xeric climates to ensure that they are net carbon sinks and do not contribute to global warming (Houdeshel, Pomeroy and Hultine 2012).

Long-term studies of nutrient treatment by vegetated and nonvegetated bioretention cells, as well as studies of the effects of cell age and temperature, are needed (Houdeshel et al. 2015). Research also is needed to determine the cause of elevated nutrients in rain garden effluent and to improve performance (Jiang, Yuan and Piza 2015). Studying nutrient uptake efficiency under different water availability scenarios might determine whether low plant and microbial activity might be limiting nitrogen uptake in bioretention cells (Houdeshel et al. 2015).

5.2.5.2. Pollutant leaching

More research is needed on leaching of metals in bioretention cells (Jiang, Yuan and Piza 2015).

5.2.5.3. Irrigation

Xeric-adapted upland vegetation showed poor nutrient retention, but wetland communities were effective in nutrient retention. Further research is needed on integrating bioretention and gray water treatment to provide a sustainable water and nutrient source for wetland communities in arid and semi-arid environments (Houdeshel et al. 2015).

5.2.5.4. Siting

Remote sensing has been used to evaluate bioretention siting options. Future work should include the use of this approach in an area with available monitored runoff data and high-resolution DEM data (Khin et al. 2016).

5.2.5.5. Design criteria

Researchers had the following recommendations for further investigations of optimal designs:

- Future studies of bioretention cells should include designs where upland vegetation can access soil water below the gravel storage layer, which may require unlined bioretention cells or deeper test cells with a layer of soil underneath the gravel layer. The shrubs used in a study of bioretention cells typically have deeper roots than the depth of the test cells. Inclusion of a liner might have artificially reduced primary productivity and the corresponding ability to remove nitrates (Houdeshel et al. 2015).
- A comparison of the phosphate treatment capacity of different media, such as expanded shale, gravel and pumice, should be made to determine whether the use of expanded shale is merited given its higher cost (Houdeshel et al. 2015).
- Vegetation density should be considered as a variable in future studies of bioretention of nutrients using upland plants (Houdeshel et al. 2015).
- More research is needed to measure transpiration and evaporation rates under xeric conditions so that facilities can be sized appropriately to meet water needs of plantings (Houdeshel, Pomeroy and Hultine 2012).

5.2.6. Vegetative filter strips

The reduction of runoff and soil loss by vegetative filter strips was assessed using models of physical processes to extrapolate from a limited empirical data set. Although this approach is preferable to an empirical analysis, future modeling work should include stochastic variation of input factors and global sensitivity and uncertainty analysis (Campo-Bescós et al. 2015).

Modeling of mitigation of pesticide loading by vegetative filter strips has been conducted (Munoz-Carpena et al. 2015). The authors suggest that to optimize models, field work is needed that considers degradation by monitoring pesticide concentrations, both within and when exiting the vegetative filter strip, over time during a series of runoff and pesticide loading events. In particular, data are needed to estimate the mass that is being deposited in the mixing layer of the filter strip.

5.2.7. Integrated systems

More pilot studies conducted in arid and semi-arid climates are needed to help stormwater managers assess the ability of integrated bioretention systems, such as combinations of rain gardens and bioswales, to remove pollutants from stormwater (David et al. 2015).

High-resolution ground surface topography from light detection and ranging (commonly known as LiDAR) would provide more accurate drainage network datasets for prioritizing remediation of degraded urban streams, addressing water quality by facilitating infiltration, and reducing high runoff volume via water retention. Including other high-resolution data (e.g., soil, DEM, impervious surface, stream network) would improve the ability of a remote sensing approach to prioritize LID. Simulating underground drainage networks in urbanized areas is a challenge, partially because of unregulated stream burial during development (Martin-Mikle et al. 2015).

5.3. Stormwater management research needs—watershed scale

To improve the use of green infrastructure for stormwater management on a watershed scale, experts have similar research recommendations as those for site-scale practices but with a greater emphasis on modeling. Prioritizing sites for installing BMPs, assessing economic viability, replicating results in other locations, incorporating high-resolution data in models, improving the mechanistic understanding of biogeochemical processes, gathering more environmental data relevant to successful installation of practices, and improving model parameterization all are important areas of study for arid and semi-arid applications of green infrastructure BMPs.

5.3.1. Land conservation

For conservation of agricultural land, research is needed on siting and economic viability. Modeling of watershed-scale implementation of BMPs suggested that fallowing irrigated land would reduce nitrate and selenium loading. For future work, researchers suggest investigating the effects of implementing BMPs—including fallowing land and enhancing riparian buffers—on a local, site-specific basis and evaluating the economic viability of alternative BMPs (Bailey, Gates and Romero 2015; Bailey, Romero and Gates 2015).

Research is needed on possible beneficial effects of land conservation on water quality in arid and semi-arid urban areas. Hale et al. (2015) modeled the effects of changing infrastructure practices on nutrient and DOC fluxes from urban watershed systems using historical data from Phoenix. The authors suggest further studies to determine the applicability of their model to other arid urban areas.

More research is needed on approaches for reestablishing vegetation in cold and dry desert environments. In a study of restoring native vegetation in a cold-arid climate, hollow frame snow fencing, which increased soil retention, improved restoration success. Further research is needed to understand the ecological drivers of the benefits of snow fencing. A better understanding also is needed of the importance of the effects of snow fencing on the duration and penetration depth of soil moisture for its beneficial impacts on revegetation. The hollow frame fence system has possible applications for managing wind and particulates in such ecosystems as hot deserts (David 2013).

5.3.2. Riparian buffers

A better understanding of the link between flow and channel degradation is needed. Modeling studies could be conducted for channels with geomorphological data to determine whether changes in flow are correlated with channel degradation. Future modeling efforts should use finer resolution data than mean daily flow to produce more precise rainfall-runoff estimates (Hawley and Bledsoe 2013).

The biogeochemical properties that affect the ability of riparian buffers to reduce pollution loading to receiving water are complex. Future work in modeling the effects of riparian buffers might involve improving the representation of riparian areas and vegetation (Bailey, Romero and Gates 2015). A better understanding of how to model spatiotemporal distribution of biogeochemical properties that influence denitrification within the riparian corridor (e.g., vegetative mix, organic carbon content, stratigraphy, hydraulic conductivity, water table fluctuation, dissolved oxygen) would enhance the ability to predict the effects of riparian corridors on nitrate loading to surface water (Bailey, Gates and Romero 2015).

To better plan riparian habitat protection and restoration efforts, more research is needed on optimal revegetation conditions, site prioritization and buffer widths. For revegetation projects, further research could involve placing piezometers directly in willow swales. It also would be beneficial to monitor seasonal soil moisture availability in depth increments between the ground surface and late summer water table (Caplan et al. 2013). Rivers produce substantial benefits for wildlife habitat, and a better understanding of channel habitats and the ecosystems they support is needed to prioritize protection of the most biodiverse river-fed lake habitats (Michalkova et al. 2011). On-the-ground monitoring is needed to further reduce uncertainty and provide a means to adjust buffer width prescriptions on timber harvesting in riparian buffer zones to meet riparian habitat protection objectives (Teply, McGreer and Ceder 2014).

5.3.3. Urban tree canopies

The source of water for urban trees generally is poorly constrained. Detailed studies of urban water budgets are needed to understand the available water sources and plan for the irrigation needs of different species of urban trees (Pataki et al. 2011).

A better understanding of modeling parameters for evapotranspiration and irrigation water demand is needed. More research is needed on urban plant evapotranspiration rates under a range of temporal and spatial conditions, such as for recently established plantings and under conditions of water stress, to develop water-conserving landscaping strategies in semi-arid urban environments (Litvak, Bijoor and Pataki 2014). Modeling efforts to predict the effects of urban residential landscapes on irrigation water demand would be improved by better parameterization of the irrigation water demand model, including more reliable water-loss coefficients for horticultural and landscape plants and the Distribution Uniformity factor, which drives excess irrigation in turfgrass landscapes (Lowry, Ramsey and Kjelgren 2011).

5.4. Stormwater conservation research needs

As for stormwater management, green infrastructure approaches to stormwater conservation in arid and semi-arid environments would benefit from replication of research studies under a variety of conditions, including geography, climate, soil type and plant species. More systematic and comparable studies are needed. Cost-effectiveness of BMPs under a variety of scales needs to be better understood.

5.4.1. Agricultural water harvesting

Given the large heterogeneity of water harvesting technologies, study sites and approaches to assessing effectiveness, more systematic and comparable studies reporting effects on crop yields are needed. Biophysical and hydrological factors, as well as farmer characteristics and crop choice, should be accounted for (Bouma, Hegde and Lasage 2016).

In a meta-analysis of rain harvesting studies conducted in Asia and Africa, Bouma, Hegde and Lasage (2016) noted that more crop yield studies have been conducted in Asia, which generally enjoys higher yields, than Africa. The authors suggest that additional studies are needed to assess possible geographic and precipitation bias, particularly for low-rainfall years in Africa. Also, studies that use a broader range of crops, especially other than maize, and under specific contexts are needed.

Future work should investigate the optimum ridge-furrow ratio and suitable ridge-mulching material for achieving the best environmental and economic benefit under different climatic conditions, soil types and plant species. More research is needed as well on using biodegradable mulching materials (Wang et al. 2015).

5.4.2. Rain barrels and cisterns

A better understanding of the scaling of the costs and benefits of rainwater harvesting systems is needed. Evaluations of costs and effectiveness at the site, neighborhood and municipal levels should be performed (Jiang, Yuan and Piza 2015). Different individual LID practices and combinations of practices, including rain barrels and cisterns, should be assessed to maximize watershed benefits with cost-effectiveness. Geographic placement and sizing of LID networks should be based on land cover and other watershed parameters (Walsh, Pomeroy and Burian 2014). A better understanding is needed for household-, neighborhood- and regional-scale rainwater harvesting systems in arid and semi-arid regions of nonmonetized benefits, such as water pollution control and community amenities; energy implication of onsite alternative water supplies; and long-term system performance and maintenance (NAS 2016).

More research is needed comparing the reliability of systems during wet and dry periods. Long-term average annual rainfall is not adequate for assessing system reliability, given seasonal and annual dry periods characteristic of arid and semi-arid regions (Mehrabadi, Saghafian and Fashi 2013).

5.5. Research themes

A number of themes for research needs apply to multiple BMPs. These research needs include the following:

- A better understanding is needed of the performance in arid and semi-arid regions of practices that have received less study under those conditions (e.g., bioswales, permeable pavement, planter boxes).
- More research is needed about long-term performance and maintenance needs under arid and semi-arid conditions.
- The mechanisms by which substrates, soil-containing or otherwise, might be a source of nutrient or other pollutant loading from the breakdown of the substrate need attention.
- The spatial scale of research on BMPs in arid and semi-arid regions should be developed more beyond pilot-scale projects.
- A better understanding is needed of how to prioritize siting of BMPs to maximize stormwater management and conservation goals, including water quality improvement.

- More testing is needed to validate models developed for temperate regions for application under arid and semi-arid conditions.
- Inclusion of higher resolution data will be important for applying proven models to arid and semi-arid environments.
- A better understanding is needed of the economic and nonmonetized benefits of stormwater management and conservation through green infrastructure practices implemented in arid and semi-arid regions at a range of scales, including site, neighborhood, municipal, watershed and regional.
- More green infrastructure research needs to be conducted in the United States to ensure that results are applicable to the specific conditions of the arid and semi-arid regions in this country.

Chapter 6.
Conclusions and Recommendations

The results of this literature review indicate that the body of current research on the design, implementation, maintenance and effectiveness of green infrastructure under arid, semi-arid and seasonally dry conditions is extensive for some practices and more limited for others. The literature on green roofs in dry or seasonally dry environments is extensive, as is research on rainwater harvesting for dryland agriculture, but relatively few studies have been published on the performance of such commonly used vegetative practices as bioswales and planter boxes. Permeable pavement, although not based on vegetation, would be expected to face unique conditions in arid and semi-arid environments, such as rapid freeze-thaw cycles, but few studies of this practice have been conducted under field conditions in these regions.

Research has tended to emphasize design over maintenance, as well as the management of stormwater quantity over stormwater quality. For example, green roofs have been studied extensively to optimize their design criteria under dry conditions, but the important question of whether substrates, soil-containing or otherwise, might be a source of nutrient or other pollutant loading from the breakdown of the substrate has received less attention.

Scale, both temporal and spatial, is an issue for applying research findings to practice. Most studies have been conducted on pilot-scale systems. The short timescales of these investigations might not be representative of the long-term performance of practices meant to last decades, such as green roofs. Implementation of green infrastructure at watershed scales might have significant differences in performance and cost-effectiveness compared with site-scale implementation. In particular, a better understanding of how to prioritize siting to optimize cost-effectiveness is needed for neighborhood- and watershed-scale implementation.

Modeling is key to planning green infrastructure implementation. More testing of models developed for temperate regions and inclusion of higher resolution data will be important for applying proven models to arid and semi-arid environments.

Finally, some of the lessons learned from international research might not be directly applicable to the United States. Vegetation native to other countries might not reflect characteristics of native U.S. vegetation adapted to conditions in arid or semi-arid regions of United States. In addition, the United States relies primarily on mechanized agriculture, and many in-field rain harvesting techniques have been developed and tested for subsistence farming. Therefore, more arid and semi-arid green infrastructure research needs to be conducted in the United States.

Green infrastructure shows great promise in its ability to store and treat stormwater in arid and semi-arid environments. Further research on effectiveness of BMPs in stormwater management, treatment and conservation under the unique conditions of these regions and at scales relevant to their implementation in the "real world" will be beneficial to developing more cost-effective approaches to stormwater regulatory compliance.

Chapter 7.
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Chapter 8.
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