JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 48, No. 6 AMERICAN WATER RESOURCES ASSOCIATION December 2012

BIORETENTION DESIGN FOR XERIC CLIMATES BASED ON ECOLOGICAL PRINCIPLES[1]

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ABSTRACT: Bioretention as sustainable urban stormwater management has gathered much recent attention, and implementation is expanding in mesic locations that receive more than 1,000 mm of annual precipitation. The arid southwestern United States is the fastest growing and most urbanized region in the country. Consequently, there is a need to establish design recommendations for bioretention to control stormwater from expanding urban development in this ecologically sensitive region. Therefore, we review the ecological limits and opportunities for designing bioretention in arid and semiarid regions. We incorporated USEPA Stormwater Management Model (SWMM) simulations to synthesize ecologically based design recommendations for bioretention in arid climates. From our review, an ideal bioretention garden area should be 6 to 8% of the contributing impervious drainage area (depending on region) with two layers of media, a 0.5-m low-nutrient topsoil layer above a 0.6-m porous media layer that acts as temporary storage during a storm event. When planted with the suggested vegetation, this design maximizes stormwater treatment by promoting ecological treatment in the topsoil while promoting infiltration and evapotranspiration of stormwater by deep-rooted shrubs that require no irrigation after establishment. This synthesis improves water resources management in arid and semiarid regions by introducing a sustainable bioretention design that protects local surface waters while reducing regional water demands for irrigation.

(KEY TERMS: best management practices; storm water management; sustainability; arid lands; urban areas planning; plant physiology.)

Houdeshel, C. Dasch, Christine A. Pomeroy, and Kevin R. Hultine, 2012. Bioretention Design for Xeric Climates Based on Ecological Principles. *Journal of the American Water Resources Association* (JAWRA) 48(6): 1178-1190. DOI: 10.1111/j.1752-1688.2012.00678.x

INTRODUCTION

Acceptance and implementation of low impact development (LID) approaches to stormwater management has increased dramatically in recent years (Davis *et al.*, 2009; Quinlan, 2010; USEPA, 2011). Green infrastructure (GI), a part of LID, is comprised of the interconnected networks of natural and constructed ecological systems within, around, and between urban areas (Tzoulas *et al.*, 2007). The expansion of these practices can be attributed to the many organizations that invested early in the LID and GI movement in both implementation and investigation of the costs and benefits of these approaches (Davis *et al.*, 2001; Prince George's County, 1999; Hunt *et al.*,

[1]Paper No. JAWRA-11-0158-P of the *Journal of the American Water Resources Association* (JAWRA). Received December 6, 2011; accepted May 29, 2012. **Discussions are open until six months from print publication.**

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2006; USEPA, 2006; Emerson and Traver, 2008; Davis *et al.*, 2009; Low Impact Development Center, 2009). These efforts have focused largely on LID and GI approaches to stormwater management in mesic climates, or climates that receive 750 to 2,000 mm (30 to 80 in) precipitation per year, to incorporate wetland remediation approaches to stormwater treatment. However, little work has taken place to modify these concepts to xeric (arid and semiarid) climates (Davis *et al.*, 2009). Implementation of GI in the xeric western United States (U.S.) is of utmost importance because this region is experiencing the greatest urban growth in the U.S. and ecological resilience is low given limited precipitation inputs and high evaporative demand (Belnap, 1995; Whisenant, 1999; U.S. Census Bureau, 2005; Claessens *et al.*, 2006; Schwinning *et al.*, 2008; USEPA, 2010a).

Bioretention is a GI practice that utilizes engineered ecosystems to store, treat, and infiltrate precipitation that falls on developed impervious surfaces. Bioretention maximizes water storage in a specifically designed garden, or series of gardens, so water can be infiltrated into the ground or transpired by plants as it would have prior to development of impervious areas (Urbonas, 2000; Hsieh and Davis, 2005; Davis *et al.*, 2009). Water is captured, treated, and in most cases, infiltrated near the area of precipitation. The known stormwater management benefits of bioretention include: reducing runoff rates and volumes from urban areas known to accelerate erosion in receiving waters; reducing pollution transported from the urban landscape into fragile aquatic habitat; reducing the need for expensive stormwater conveyance systems; and flood control during large precipitation events (Brix, 1993; Roesner, 2001; Pomeroy and Roesner, 2007; Emerson and Traver, 2008; Davis *et al.*, 2009; Zhang *et al.*, 2011). Bioretention creates an opportunity to expand green space in urban settings, which makes a city more attractive and may act as a local carbon sink (Pataki *et al.*, 2006). Additionally, if bioretention is installed as an alternative to traditional landscaping, implementation of bioretention and other GI stormwater management approaches may relieve emerging stress on regional water supply in xeric locations by creating an attractive no-irrigation landscaping alternative.

Currently, there is a conspicuous lack of information available in the stormwater management literature addressing bioretention in xeric climates (NRC, 2008). Therefore, in order to initiate dialogue-addressing guidelines for bioretention in xeric regions, this study combines designs of bioretention in mesic climates with literature describing plant ecophysiology, arid land ecology, wildland restoration for arid regions, and hydrologic modeling. Design guidelines are then synthesized to create an ecologically based stormwater management system capable of thriving in harsh western climates while simultaneously treating urban runoff and utilizing stormwater as the primary irrigation source.

THE NEED FOR BIORETENTION FACILITIES IN XERIC URBAN LANDSCAPES

The extent of urbanization has been suggested as the most dominant factor altering the water budget at local and regional scales (Claessens *et al.*, 2006). Locally, urbanization is stated by the U.S. Environmental Protection Agency (USEPA) to be the greatest cause of impairment to surface water quality (USEPA, 2010b). Regionally, urban spread in xeric climates increases water demand by increasing population and increasing the area of land irrigated for lawns and gardens (Eriksson *et al.*, 2002).

To continue addressing the challenges of managing stormwater runoff associated with urbanization, the USEPA has recently initiated national rulemaking to reduce stormwater discharges from new development and redevelopment and make other regulatory improvements to strengthen its stormwater program (USEPA, 2011). As part of this rulemaking, GI is being emphasized for its ability to reduce the magnitude of water cycle modification in urban areas, as well as its ability to reduce pollutants in stormwater runoff. The National Resource Council (NRC) has also emphasized that stormwater control measures that utilize engineered ecosystems, including LID, to harvest, infiltrate, and evapotranspire stormwater, are critical to reducing the volume and pollutant loading of small storms (NRC, 2008).

Bioretention utilizes soils and plants to remove pollutants from stormwater runoff (USEPA, 2006; Davis *et al.*, 2009). Currently, a number of bioretention design guidelines are available as references for planners and designers (Prince George's County, 2001; USEPA, 2006; Low Impact Development Center, 2009). These guidelines focus on bioretention design in mesic systems, and address traditional stormwater engineering approaches such as facility sizing and hydraulics design. The NRC also highlighted the need to expand study of relevant hydrologic and water-quality processes across different climates and soil conditions (NRC, 2008). The aforementioned LID and GI guides do not provide appropriate information to assist designers in solving the stormwater management challenges that accompany the forecasted urbanization in xeric climates.

The challenge of mitigating the negative effects of urbanization on surface waters through GI is further compounded in xeric climates because the native ecosystems are less resilient to recover from anthropogenic influence (Belnap, 1995; Schwinning *et al.*, 2008). Additionally, ecological remediation opportunities are limited by water availability in xeric regions (Heady and Child, 1994; Knapp *et al.*, 1998; Whisenant, 1999; Barbour and Billings, 2000). States dominated by xeric climates have the fastest growing populations in the country (U.S. Census Bureau, 2005); this growth will have profound impacts on the water cycle at the local and regional scale.

To compound the difficulties of managing water for large, growing populations in sensitive xeric climates, global climate models have predicted that the Colorado River will suffer a reduction in streamflow due to climate forcing caused by anthropogenic inputs of CO_2 and other greenhouse gasses to the atmosphere (Barnett *et al.*, 2004; Christensen and Lettenmaier, 2007; USDOI, 2007; Barnett and Pierce, 2009). The Colorado River provides water to 27 million people and drives significant sectors of the economies of Colorado, Utah, Arizona, Nevada, southern California, and Mexico (Barnett and Pierce, 2009). Consumptive diversions have prevented almost all flow from reaching the Sea of Cortez since the beginning of the construction of the Hoover Dam in the 1930s (Carriquiry and Sanchez, 1999). These regional predictions of rapid growth and reduced water availability emphasize the need to manage stormwater to protect ecosystems stressed from a changing climate and to reduce regional water demand by managing stormwater as a resource.

Over half of the water use within major urban centers in northern Utah and southern California is irrigation of landscaping (Eriksson *et al.*, 2002; Salt Lake City, 2010). In xeric climates, implementing GI in place of traditional landscaping provides an opportunity to reduce water demand per capita, thus allowing more growth under constrained resource availability. An integrated approach to stormwater management and water supply in xeric climates allows protection of the region's scarce surface waters by reducing the threat of physical and chemical damage to waterways from urban runoff and the demand these waters must satiate.

PROPER PLANT SELECTION FOR LID FACILITIES IN XERIC CLIMATES

In xeric climates, water is a limited resource. The vast majority of the Desert Southwest, including southern California, Nevada, Utah, Arizona, New Mexico, and western Texas receive <380 mm of rainfall each year. This creates a unique challenge as few species suggested for use in bioretention in more mesic climates can survive the dry conditions common in the arid West. Looking to the extensive work that has been done in ecological restoration can close the gap on this challenge by providing a framework for plant selection. Ecological restoration is a discipline that focuses on how to reestablish plants in order to repair damaged hydrological functions in wildlands (Heady and Child, 1994; Knapp *et al.*, 1998; Whisenant, 1999; Holecheck *et al.*, 2004). Recommendations for plant selection for LID in xeric climates are limited, but recommendations for plant selections for ecological restoration in xeric climates are abundant. Plant selection for ecological restoration is based on matching physiological plant traits with site conditions to repair damaged hydrologic functions in wildlands (Heady and Child, 1994; Knapp *et al.*, 1998; Whisenant, 1999; Holecheck *et al.*, 2004). The common focus on renovating the hydrologic cycle shared between the use of bioretention for urban stormwater management and ecological restoration enables designers of bioretention to draw from the extensive work done by restoration ecologists to restore predevelopment hydrology to urban landscapes.

Within xeric climates of the western U.S., two distinct precipitation patterns drive equally distinct vegetative communities (Figure 1). The Great Basin and Intermountain West, encompassing the Salt Lake City, Utah; Boise, Idaho; and Denver, Colorado, urban centers are "cool" deserts, where precipitation typically falls in the winter or spring as snow (MacMahon, 2000). Plants depend on soils to store moisture until the growing season when temperatures are warm

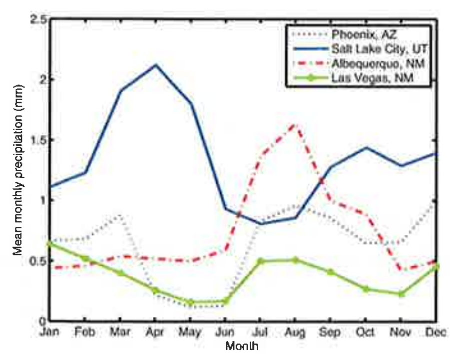

FIGURE 1. Precipitation Patterns for Four Arid to Semiarid Western Cities. Salt Lake City receives the majority of precipitation in the winter and early spring where Phoenix and Albuquerque receive most of their precipitation in late summer. Las Vegas not only receives some precipitation as summer monsoons, but also receives some precipitation from large frontal winter storms with no consistent wet season.

enough to allow plant activity. Growth is rapid in spring and quickly decreases for many shallowly rooted species as soils dry. Coastal southern California experiences the same pattern of precipitation delivery except that average winter temperatures are well above freezing. Conversely, Arizona, western Texas, New Mexico, and southern Utah are regions that are considered "warm" deserts, or deserts that receive the majority of the annual precipitation as rain in phase with the growing season (MacMahon, 2000). The Mojave Desert in eastern California and southern Nevada is transitional, as this region is affected by both of the above patterns. Las Vegas is the largest urban area in this climate regime.

Plants in xeric climates have adapted to surviving in low-water environments by evolving mechanisms that control water transport within the plant. Plant water transport is driven by water potential (Ψ) gradients through the soil-plant-atmosphere continuum. Water flow through the plant is initiated as the stomata (small pores on the leaf surface that allow gas exchange) open, allowing water to evaporate from the moist leaf to the drier atmosphere, thereby reducing leaf Ψ below soil Ψ (Elfving *et al.*, 1972; Zimmermann, 1983). Low atmospheric Ψ evaporates water from the stomata lens, which pulls water from the soil into the roots, through the xylem to the leaf surface. If this pathway is broken by cavitation, most plants lose the ability to take up water from the soil even if soil moisture becomes adequate to allow transport, and the plant dies. Plants can control leaf surface area characteristics and the rate of water flow by controlling the aperture of the stomata, allowing more or less water to evaporate from the leaf to maintain a suitable Ψ gradient (Tyree and Sperry, 1989; Sperry *et al.*, 2002).

In xeric climates, plants are stressed by both the limited amount of moisture in soils and by the limited amount of moisture in the atmosphere. Low soil moisture combined with low atmospheric water content increases a plant's risk of cavitation of liquid water in the conduits of plants (i.e., the entry of gas bubbles into conduits that normally transport water to the leaves) as a result of extreme Ψ gradients between the leaf-atmosphere interface and the root-soil interface. Freezing of the water in the xylem is another stress plants in xeric climates are exposed to that can lead to cavitation. Ice crystals can act to catalyze the formation of bubbles in the low pressures in the xylem, or the formation of ice within a vessel can concentrate dissolved gas beyond the saturation point, creating bubbles that cause cavitation.

Distinct native plant communities have evolved to maximize productivity in each desert region. These communities are physiologically adapted to minimize the greatest risk of xylem cavitation and subsequent leaf desiccation and plant mortality in their respective region. In addition to the different patterns of precipitation delivery and related ψ stresses described above, sensitivity to cold has also influenced plant distribution across xeric landscapes. Cold desert species are exposed to frost damage because of colder temperatures when soil moisture is available in winter and spring. One common strategy to limit frost damage in winter is to shed leaves, but this limits photosynthetic capacity in early spring when temperatures are commonly warm enough for photosynthesis but freezing is still common. Other strategies employed by evergreen shrubs such as *Artemisia tridentata* (sagebrush) and *Cercocarpus ledifolius* (curl-leaf mountain mahogany) include: concentrations of phenols and salts in the leaf to lower the freezing temperature of water; insulating the xylem with thick bark to reduce the risk of ice formation, decreasing xylem diameter and other architectural techniques that compromise hydraulic conductivity for resiliency if freezing damage does occur, and refilling the xylem through positive root pressure in the spring (Sperry *et al.*, 1987; Sperry and Tyree, 1988; Tyree and Sperry, 1989; Sperry and Sullivan, 1992). The development of these strategies allows plants in cold deserts to photosynthesize early in the growing season when water is available, then close down water transport through the dry months, thus avoiding the risk of cavitation due to extreme Ψ gradients in summer. Mojave Desert species can "green up" or produce new leaves with adequate temperature and soil moisture at any time of year, and drop their leaves when the soil dries. In all cases, the plant avoids cavitation by developing mechanisms that allow photosynthesis when water is available and protect against the potentially harmful temperatures that accompany water availability.

Bunchgrasses are common in arid and semiarid ecosystems, and are known to have high transpiration rates over short growing seasons. The growing season of a grass is described as warm season or cool season, indicating geographic range and physiology. Cool season grasses are most productive in spring when temperatures are moderate and soil moisture is abundant because enzymatic and biochemical limits reduce photosynthetic efficiency per water use in hot weather. Warm season grasses utilize a more evolved photosynthetic pathway and are most productive when high temperatures are coupled with summer precipitation. When growth conditions deteriorate, bunchgrasses drop their seeds and go dormant until either temperature or soil moisture is again optimal for growth.

Root structure is also varied among western desert plant species in different temperature regimes. Two rooting patterns are most common: phreatophytes, or plants with large, deep tap roots to access groundwater sources year round, or plants with shallow and extensive, wide spreading root networks (Stubbendieck *et al.*, 1997; West and Young, 1999; Whisenant, 1999; Holecheck *et al.*, 2004). Rooting depths of phreatophytes including *Chrysothamnus nauseous* (rubber rabbitbrush), *Atriplex confertifolia* (shadscale), *Quercus gambelii* (scrub oak), and *Prosopis glandulosa* (mesquite) are known to exceed 30 m, including a recorded depth in excess of 50 m (Canadell *et al.*, 1996); roots of cool season shrubs are commonly four to nine times the above-ground biomass (Rodin and Bazilevich, 1967; Fernandez and Caldwell, 1975; Jackson *et al.*, 1996). Phreatophytes thrive by utilizing deep soil water other plants cannot access in climates where prolonged droughts and seasonal dry periods in summer or shallow salt accumulations are common. Desert shrubs that cast extensive root networks through shallower soils, such as *Larrea tridentata* (creosote bush), *Pinus edulis* (piñon pine) and *Arctostaphylos* sp. (Manzanita), quickly capture and utilize small precipitation events during the growing season (Kummerow *et al.*, 1977; Brisson and Reynolds, 1994; West *et al.*, 2007). Some shrubs including *A. tridentata* (sagebrush), *Prosopis velutina* (velvet mesquite), and *Juniperous occidentalis* exhibit deep taproots and shallow, extensive root networks (Miller *et al.*, 1990, 2005; Hultine *et al.*, 2004). Shrubs with deep tap roots and shallow root networks such as *A. tridentata* and *Prosopis velutina* have been shown to lift water from deep, saturated soils to shallow, dry soils at night when the plant does not need the water to drive photosynthesis or gas exchange, making water available to transpire the following day by either itself or neighboring plants such as bunchgrasses (Richards and Caldwell, 1987; Hultine *et al.*, 2004).

Directly related to root growth is the presence of arbuscular mycorrhizal fungi (AMF) in soils. As root length increases, opportunities for interactions with AMF increase (Treseder and Turner, 2007), increasing the ability to absorb nutrients and help sustain plants in xeric systems (Gianinazzi-Pearson, 1996; Requena *et al.*, 2001; Tao and Zhiwei, 2005). Soil structure and infiltration rates are also improved by AMF. The fungi exude glomalin, a sticky protein that improves soil stability by holding soil aggregates together during wetting and drying cycles (Wright and Upadhyaya, 1996).

GI and wildland restoration both strive to restore natural hydrology to a compromised site; however, GI has a great advantage in achieving this goal because the facility is engineered and many variables can be controlled. Soil texture, moisture regimes, and land use are often all out of the control of the restoration ecologist. But the engineer can dictate plant selection by choice of growth media, can adjust moisture amounts by adjusting drainage size to supply water to the site, and can erect permanent barriers such as curbing to protect the site from trampling. A basic understanding of plant-water relations and physiological plant traits can greatly increase the opportunity for a successful GI installation.

DESIGN RECOMMENDATIONS

Currently, a number of bioretention design guidelines are available as references for planners and designers (Prince George's County, 2001; USEPA, 2006; Low Impact Development Center, 2009). Reviewing these references demonstrates that, to date, designing LID bioretention has concentrated on mesic systems and addresses traditional stormwater engineering approaches such as facility sizing and hydraulics design. In addition to these parameters, selecting appropriate plants for a bioretention can enhance facility performance by promoting natural ecological processes and play an equally critical role in the success or failure of the facility. Plant selection suggestions for mesic landscapes are provided in currently available reference materials (Prince George's County, 2001; USEPA, 2006; Low Impact Development Center, 2009), but are insufficient to assist designers that are not familiar with the ecological intricacies of xeric climates.

Based on physiological traits and differences in water use, a mixture of bunchgrasses and shrubs will maximize the functional treatment benefits offered by plants within a bioretention facility. Grasses can demonstrate extensive root growth up to 0.6 m and can re-grow up to six sets of roots to this depth per growing season (Knapp *et al.*, 1998). The re-growth of roots creates many small channels for water rushing onto the surface of a bioretention facility to rapidly infiltrate through the topsoil layer to the storage layer, which minimizes ponding time and maximizes capture efficiency. Grass roots also form an extensive net that interfaces with AMF, forming a dense web stabilizing soils and filtering water as it flows through. Deep-rooted shrub roots can access deep-water pockets that are unavailable to grasses (Richards and Caldwell, 1987; Canadell *et al.*, 1996; Knapp *et al.*, 1998; Wilcox *et al.*, 2003). Shrubs have fine roots that turn over to improve infiltration and perennial roots that do not turn over that can grow to great depths. Select shrubs can root through the bioretention cell and penetrate the native soils below, encouraging infiltration. Canadell *et al.* (1996) reports that many shrubs in xeric climates grow roots exceeding 5 m, and can grow through many types of media. The process of hydraulic lift facilitated by a wide range of deeply rooted plant species may serve to irrigate bunchgrasses with shallower root systems that cannot directly access deep, seasonally stored water. Mimicking nature by combining deep-rooting shrubs with extensive, shallow-rooting grasses should provide the maximum hydraulic stormwater function and drought tolerance potential for a bioretention garden.

Plant roots play critical roles in the ability of bioretention to infiltrate, transpire water, and absorb nutrients in all soil textures. Increased root growth increases infiltration by creating macropores as roots grow and turn over (Knapp *et al.*, 1998; Whisenant, 1999). Sandier soils encourage more expansive root growth because as average soil particle size increases the soil's physical ability to store water and nutrients decreases, forcing the plants to mine deeper into the soil to find water and nutrients (Klinge, 1975, Cuevas and Medina, 1986; Nagaraja, 1987; Silver *et al.*, 2000). Infiltration rates through coarser media are high without plants, and although less root growth may occur in fine soils, plants have a greater effect on infiltration rates in fine soils. Undeveloped, fine soils with low organic content have low inherent infiltration rates (e.g., Wilcox *et al.*, 1992). Plant roots also provide hosts for AMF, further improving soil structure. Fine-textured soils that are well developed through the addition of organic matter and established macropores can exhibit infiltration rates much greater than bulk mineral soil of the same texture.

Selecting appropriate plants for use in bioretention in xeric climates must be addressed regionally because stresses to plants are unique to each desert region. A summary of plant species, ecological traits, and appropriate regions of use in bioretention are given in Table 1 and shown in Figure 2. In general, warm season bunchgrasses should be planted in concert with locally native shrubs and evergreens in warm deserts, and a mixture of warm season and cool season bunchgrasses should be planted with locally native shrubs and evergreens in cool deserts. Commercial plant availability can dictate plant selection; however, proper planning can allow suppliers to order desired species from growers if the demand for a particular species is high.

Spring or summer plantings in all regions will require intensive weekly irrigation during the first year of establishment to help root systems develop sufficiently to access deeper pockets of soil moisture. After the first year, the plants suggested in Table 1 will survive and grow in each plant's recommended region without supplemental irrigation. The plants suggested are slow-growing species under natural moisture regimes. Because of the low growth rates, leaf turn

TABLE 1. Recommendations for Plants to Be Used in Bioretention in Arid Climates.

Species Name	Common Name	Form	Rooting Pattern	AMF Host	Recommended Region
Schizachyrium scoparium	Little bluestem	WG	E	Likely	1,2,3,4
Bouteloua gracilis	Blue gramma	WG	E	Likely	1,2,3,4
Sorghastrum nutans	Indiangrass	WG	E	Likely	1,2,3,4
Pascopyrum smithii	Western wheat grass	CG	E	Likely	1
Pseudoroegneria spicata	Bluebunch wheat grass	CG	E	Likely	1
Rosa woodsii	Wood rose	S	E	Likely	1,2,3,4
Rhus Aromatica	Fragrant sumac	S	E	Yes	1,2,3,4
Fallugia paradoxa	Apache plume	S	E	Likely	1,2,3
Chrysothamnus nauseosus	Rubber rabbitbrush	S	P	Likely	1,2,3
Atriplex canescense	Four-winged saltbrush	S	P	Likely	1,2,3
Juniperus osteosperma	Utah juniper	T	E and P	Yes	1,2,3
Cercocarpus ledifolius	Curly mahogany	S, T	P	Likely	1,2
Larrea tridentata	Creosote	S	E	Likely	2,3
Artemisia tridentata	Sagebrush	S	E and P	Yes	1,2
Cercocarpus montanus	Mountain mahogany	S, T	P	Likely	1,3
Eschscholzia californica	California poppy	F	E and P	Unknown	1,4
Epilobium angustifolium	Fireweed	F	E	Yes	1,4
Baileya multiradiata	Desert marigold	F	P	Unknown	2,3
Eschscholzia glyptosperma	Desert poppy	F	P	Unknown	2,3
Tulipia sp.	Tulips	F	Bulb	Unknown	1
Arctostaphylos glauca	Bigberry manzanita	S, T	E	Likely	4
Solidago californica	California goldenrod	S	E	Likely	4
Delphinium bicolor	Low larkspur	F	E	Unknown	1

Notes: Recommendations are based on literature review and favorable plant traits. Rooting pattern codes signify: E, shallow, extensive; P, phreatophyte; B, bulb. In the Form column: G, bunchgrass; S, shrub, T, tree, F, perennial flowering forbs. In the Recommended Region column: 1. Basin and Range (Salt Lake City, Boise, Denver); 2. Mojave (Las Vegas); 3. Warm Deserts (Phoenix); and 4. Coastal southern California (Anaheim and San Diego, California).

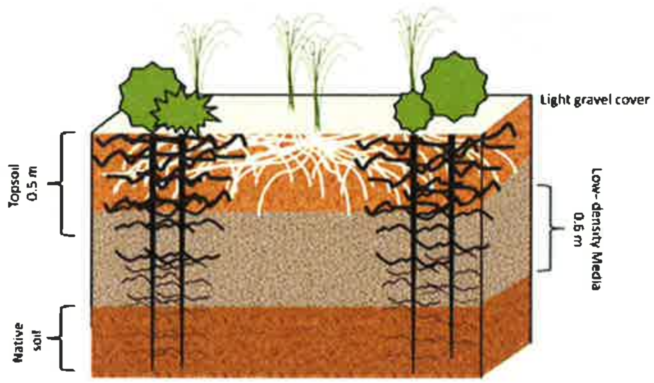

FIGURE 2. Design Recommendation for Bioretention in Arid Climates. Regionally native bunchgrasses and shrubs planted in 0.66 m topsoil over 0.66 m of low-density fill with light-colored gravel on top of a weed barrier to protect the surface from erosion damage. Dark roots represent deep-rooted shrubs; white roots represent bunchgrass roots.

over and maintenance is expected to be low. Trimming bunchgrasses to a height of 10 cm each winter will promote new shoot growth the next growing season.

PHYSICAL DESIGN PARAMETERS FOR BIORETENTION IN XERIC AND SEMIARID CLIMATES

Before GI can be used to replicate and restore natural hydrology to a site, the natural hydrology of that site must be well understood (Whisenant, 1999). In warm deserts, precipitation falls onto highly permeable sands and is rapidly returned to the atmosphere by evapotranspiration or infiltrated into groundwater storage and produces very little overland flow for small events, but high-intensity events that saturate shallow soils frequently cause flash flooding (West and Young, 1990; MacMahon, 2000; Barbour and Billings, 2000; Hirschman and Kosco, 2008). In cold deserts, very little precipitation falls during the growing season, but because of snow storage, infiltration, and localized groundwater storage, moisture is often available to plants throughout the hot summer (Ehleringer *et al.*, 1991; Knapp *et al.*, 1998; Whisenant, 1999; Barbour and Billings, 2000). As snow melts during warm periods in the winter and spring, a great deal of water is infiltrated into the soils. Spring rains fall on the wetted soil and rapidly infiltrate to feed local aquifers and almost no runoff is produced (Wilcox *et al.*, 1990, 1992). Water slowly percolates to feed base flow in nearby streams or is locally stored in pockets of deep soil water and available to the native, deep-rooted plants through much of the summer (Donovan and Ehlringer, 1994; Linton *et al.*, 1998). Fall precipitation provides water for seed germination before winter and establishment of new plants in spring.

After development of land, impervious surfaces prevent precipitation from infiltrating where it lands. Bioretention is intended to provide a pathway for precipitation that falls on vast impervious surfaces to infiltrate into the groundwater system at designated points. In order to accomplish this hydraulically, short-term storage must be engineered to allow a large volume of water to infiltrate over a relatively small footprint. Modifying the design recommendation from Hsieh and Davis (2005) so that a storage layer of gravel or expanded shale media replaces the "filtration layer" consisting of sand and sandy loam soils is an efficient way to achieve this temporary storage space. Precipitation runoff can then be routed to the gravel storage reservoir and then slowly infiltrated into the native soils below, where small pockets of underground storage will naturally form. Appropriately selected native plants can root through the gravel storage reservoir and into the native soils to access these small pockets through the summer months. The storage layer will be oxygen limited when saturated and should promote denitrification before infiltration (Hunt *et al.*, 2010; Lucas and Greenway, 2010). Deep-rooting shrubs can provide carbon to microbes below the storage level, promoting nutrient immobilization as water infiltrates below the storage layer.

Mulch is commonly prescribed as a soil covering of bioretention because of its ability to sorb pollutants from stormwater (Dietz and Clausen, 2005; Hsieh and Davis, 2005; Davis *et al.*, 2009). However, mulch requires frequent maintenance and replacement. In xeric climates, mulch becomes sun-faded and loses its esthetic quality, then must be disposed of and replaced because the dry conditions do not provide an environment that promotes decomposition (Sue Pope, Landscape Maintenance Supervisor, University of Utah, 2010, personal communication). Decorative gravel is often twice the cost to install compared with bark mulch. However, 4 to 10 cm of cobble or gravel does not need to be replaced and does not require clean-up or maintenance after a large flood event because it does not float. Further, light-colored rock covering can increase the albedo, or solar radiative reflectance, of a site and decrease surface temperatures relative to bark mulch-covered areas, reducing water demand for the plants (Montague and Kjelgren, 2003). In spite of the higher cost of installation, using gravel as a top layer reduces maintenance, and therefore lessens the whole life cost of the facility (Houdeshel *et al.*, 2011).

Researchers have expressed concern that nutrient-rich topsoil installed in bioretention leaches nutrients into surface waters (Dietz and Clausen, 2005; Hunt *et al.*, 2006; Davis *et al.*, 2009). Many plants native to xeric climates are adapted to a wide range of soils with high infiltration rates maintained by ecological influences and low nutrient content (Wilcox *et al.*, 1990, 1992; Whisenant, 1999; Barbour and Billings, 2000). Therefore, a sandy loam topsoil of low nutrient content, similar to the recommendations summarized in Davis *et al.* (2009), is recommended for bioretention in xeric climates. The native soils excavated from the site are likely sufficient to grow locally native plants. Using *in situ* soils reduces costs associated with hauling and reduces transport of required resources to the site, improving the sustainability of the project. If *in situ* soils are high in clay content, mixing sand or top-soil with the native soils may be preferred to improve infiltration, but upon establishment, the engineered ecosystem is expected to maintain high infiltration rates even in high-clay soils (Wilcox *et al.*, 1992).

Sizing the storage layer appropriately is crucial to the functionality and cost of the facility. As size increases, so do costs associated with excavation and imported fill materials (Houdeshel *et al.*, 2011). If a storage layer in a cold desert is undersized, the facility cannot infiltrate enough runoff in the spring to sustain plants through the summer. This is less of a concern for warm deserts because the rain falls during the growing season and plants transpire the moisture as soon as it falls. However, the storage layer should not be reduced because warm deserts often experience larger storms at greater intensities than cold deserts (Hirschman and Kosco, 2008) and downstream physical and ecologic impacts of increased flow rates and volumes as a result of urbanization on receiving waters has been well documented (Hollis, 1975; Brix, 1993; Roesner, 2001; Pomeroy and Roesner, 2007; Emerson and Traver, 2008; Davis *et al.*, 2009). The physiological restraints of plants, rather than cost, should decide storage layer design for xeric regions. Many shrubs and trees adapted to arid climates are known to root through thin gravel layers to access deeper soil moisture. However, increasing the depth of the storage layer may restrict the ability of some species to successfully root through the storage layer. Because of this, a standardized storage layer depth of 0.6 m is recommended for both warm deserts and cold deserts to maximize storage efficiency and to best facilitate plant performance.

Based on these concepts, we recommend a bioretention design modified from Hsieh and Davis (2005) that includes a gravel storage layer to maximize storage capacity instead of sand. Our recommendation for an unlined bioretention cell includes, from the bottom up, a 0.6-m gravel storage layer, a 0.5-m top-soil layer, weed barrier, and a 0.03- to 0.10-m decorative gravel on top (Figure 3). The storage layer provides short-term storage volume during and after precipitation and/or melting events to allow infiltration of a large drainage area over a small footprint. The topsoil layer provides a media for plants to establish during the first year, and to develop an extensive web of roots to facilitate AMF that will capture and store nutrients that flood the site. The weed barrier acts to reduce evaporative losses and prevent unwanted weeds that can rapidly deplete soil moisture content (Mack, 1981). Light-colored decorative gravel is prescribed here instead of mulch to reduce maintenance, fortify the site against damage during flooding, and reduce albedo. Mixtures of sizes, colors, and textures can be used to achieve a desired appearance or architectural objective. Large boulders can also be placed within the facility and curbing can be placed around the facility to protect vegetation against trampling.

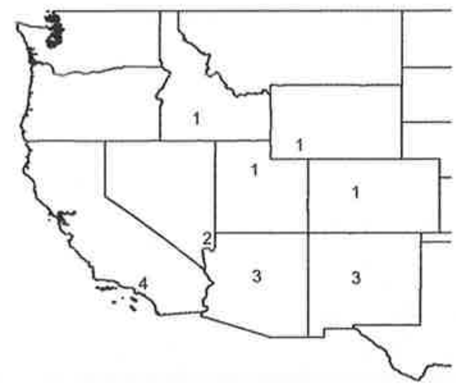

FIGURE 3. Map Displaying Relative Geographic Locations of Recommended Regions in Table 2.

BIORETENTION SIZING RECOMMENDATIONS

Bioretention and other LID approaches to stormwater management are typically sized to capture small, frequent rain events (Hunt *et al.*, 2006; USEPA, 2006; Davis *et al.*, 2009) because research suggests capturing the initial flush from an impervious surface can greatly reduce pollutant loading to surface waters (Davis *et al.*, 2009) and because small, frequent floods cause more damage to streams than large, infrequent floods (Hollis, 1975). However, the Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects under Section 438 of the Energy Independence and Security Act of 2007 (EISA) requires that federal projects "manage on-site the total volume of rainfall from the 95th percentile storm or managing on-site the total volume of rainfall based on a site-specific hydrologic analysis" to meet predevelopment hydrology (USEPA, 2009). The 95th percentile "storm" is 20 mm over one day for Salt Lake City and 25.4 mm over one day for Phoenix, Arizona, according to the methods recommended by USEPA (2009) and explained by Hirschman and Kosco (2008).

In order for urban water managers in xeric climates to understand which measure of control is most appropriate, the natural hydrology of each site must be evaluated. A generalization can be made from a study by Wilcox *et al.* (1990) that measured the annual runoff from two predevelopment sites in southeastern Idaho and Arizona. The Idaho site was the characteristic of a Great Basin sagebrush grassland (cold desert) averaging 240 mm of precipitation annually over 20 years and the Arizona site was the characteristic of a Sonora Desert shrubland (warm desert) averaging 267 mm of rainfall annually over 7 years. Wilcox *et al.* (1990) found that, during the research period, the cold desert produced an average 2 mm of runoff per year and the warm desert produced an average of 20 mm of runoff each year (Wilcox *et al.*, 1990).

Once the natural hydrology of a region is understood, a system can be engineered to mimic the natural processes driving this hydrology. Based on the physiological needs of regionally appropriate plants, we recommend a 0.6-m depth for the bioretention storage layer. Given a constant storage depth, a garden area-to-drainage area (GA:DA) relationship can be developed for various storm depths if the precipitation to runoff relationship (P:R) is defined.

Many LID design references that are currently available suggest that bioretention sizing be based on results from a single design storm that targets a statistically determined storm depth over a given time (Prince George's County, 2001; North Carolina State University, 2011; LID-Stormwater.net, 2011); however, long-term simulations are now being encouraged as more appropriate (Sitler and Clark, 2011). The results of both approaches are compared in order to recommend an appropriate DA:GA ratio for xeric climates. The TR-55 method expresses ground surface conditions by a unitless curve number, where highly impervious, smooth surfaces receive a number close to 100 (concrete pavement = 98) and pervious, rough surfaces where runoff is slow are assigned lower numbers (healthy meadow = 30), then predicts runoff as a function of precipitation inputs, drainage area, and ground surface condition (U.S. Department of Agriculture, 1986). The TR-55 method was used to calculate GA:DA relationships for a warm desert site and a cold desert site because the EISA requires that a bioretention facility be sized to treat the 95th percentile "storm," and the TR-55 method is referenced as the appropriate method for this type of analysis in bioretention design guidelines (Prince George's County, 1999; North Carolina State University, 2011; LID-Stormwater.net, 2011). Results and assumptions used in the TR-55 calculations are given in Table 2.

TABLE 2. When Calculating the Required Storage Volume for a Given Runoff Depth (Q), the Area of the Bioretention Cell Scales Linearly with Drainage Area.

	Phoenix	Salt Lake City
95th percentile "storm" (mm)	25.4	20
Calculated Q from TR 55 (mm)	20	15.2
Storage layer depth (m)	0.2	0.2
Porosity of storage layer (%)	40	40
DA:GA	12:1	16:1

Notes: If design parameters of the bioretention cell are constant (media depth, vertical sides of storage layer, and homogenous porosity of storage media), garden area (GA) can be expressed as a percentage of drainage area (DA) for a given Q.

Continuous modeling should be used in addition to single storm event modeling to verify that a bioretention facility is sized appropriately to satisfy site management goals (Sitler and Clark, 2011). In order to compare the long-term results of bioretention facilities sized according to the EISA requirements, the USEPA Storm Water Management Model 5.0 (SWMM) was used to conduct a 20-year continuous simulation (1990 to 2010) for a Great Basin site and a Sonora Desert site. A storage unit with infiltration and an overflow outlet was used to model the bioretention units. Precipitation data from Salt Lake City (NOAA Station 427598) were used to represent cold desert precipitation and guide design parameters; precipitation data from Phoenix (NOAA Station ID 026481) were used to represent warm desert precipitation and guide design parameters. Model parameters used to simulate the bioretention cells for the warm desert and cold desert are given in Table 3. Results are reported in Table 4. From this analysis, the recommendations for sizing a bioretention facility according to the 95th percentile storm match

TABLE 3. Modeling Parameters Used to Simulate Long-Term Performance of the EISA Stormwater Management Regulations for Warm (Phoenix) and Cool (Salt Lake City) Deserts.

	Phoenix	Salt Lake City
GA as % of DA	8.4	6.3
Functional storage layer depth (m)	0.08	0.08
K_s of storage unit	24.1	30
S_f of storage unit	79	72
Initial deficit	0.15	.015

Note: Infiltration parameters used for the warm and cool desert models were taken from the results of Wilcox *et al.* (1990, 1992), respectively.

TABLE 4. Results from Continuous SWMM Results to Measure Long-Term Performance of a Bioretention Cell Sized According to EISA Guidelines for Salt Lake City.

	Phoenix			Salt Lake City		
Annual average runoff to bioretention (m^3)		1,997			3,862	
GA as % DA	11	8.4	7	6.3	5	4
Annual average capture (%)	98.4	95.5	92.6	99.8	97.2	94.2

Note: Infiltration parameters for bioretention facilities represent ungrazed sagebrush grassland as measured by Wilcox *et al.* (1992).

predevelopment hydrology for Salt Lake City because predevelopment hydrology produces little to no surface runoff. However, if the goal of the facility is to capture 95% of the annual postdevelopment runoff, then the TR-55 method will oversize the facility. The long-term model shows that capturing the 95th percentile storm captures 95% of the annual runoff for Phoenix, but does not match the 20 mm of annual runoff measured by Wilcox *et al.* (1990). In order to achieve an annual runoff of 20 mm, the DA:GA must be no greater than 9:1 and would capture 98% of total annual runoff.

BIORETENTION UNDER PRIOR APPROPRIATIONS WATER LAW

Much of the western U.S. is governed by prior appropriations water law, a system that grants water use rights based on the doctrine of first in time first in right, where the first user to put the water to a beneficial use acquires a valid water right. There have been concerns that LID and GI may interfere with this allocation system because LID and GI methods generally capture water without a right and infiltrate it into the groundwater, thereby altering the delivery to the allocated user. However, the intention of a bioretention facility specifically is to treat runoff and to restore the hydrology of the site to predevelopment conditions – not put the water to a beneficial use. Most water rights were established in the early 1900s, before modern urbanization. Therefore, bioretention facilities should improve the quality of the water delivered to the allocated rights holder and help to restore the initial timing of delivery to better match the original right. Bioretention should benefit rather than impair the downstream user by delivering cleaner water in a natural runoff time scale. Because bioretention system is not putting water to a beneficial use, it should not interfere with the prior appropriation water law system.

CONCLUSION

The survey of bioretention, plant physiology, and wildland restoration supported by leaf gas exchange measurements and hydrologic modeling exercises presented here suggest that if bioretention system design is ecologically based, then bioretention can be utilized to mitigate negative effects of urban stormwater runoff and reduce per-capita water demand by providing a zero-irrigation alternative to traditional landscaping. Addressing both stormwater runoff and easing demand for regional water resources will benefit the fragile desert ecosystems that surround the fastest growing population centers in the country.

More research is needed to measure transpiration and evaporation in bioretention cells in all climates, but given the high vapor pressure deficit of xeric climates, evaporation rates likely account for a significant loss in bioretention systems. Knowing evapotranspiration rates over the course of the growing season can help to optimize facility sizing to more precisely supply the water needed to sustain plants that provide stormwater treatment. The carbon budgets of these systems are also of concern. More research is needed to confirm that the wetting and drying experienced by bioretention in xeric climates are net carbon sinks and not contributing to global climate change driven by increased atmospheric CO_2 or N_2O levels. When these relationships are quantified at the garden scale, models can be developed to predict urban effects on carbon sequestration, water savings, and stream health improvements. With a better understanding of how bioretention might affect these regional issues, water resources managers can better decide the appropriate rate and scale to which bioretention should be implemented in xeric systems.

ACKNOWLEDGMENTS

This research was conducted under the support of the University of Utah Sustainable Campus Initiative Fund and the National Science Foundation under Award Number CBET-1133524. The authors also acknowledge Megan Houdeshel, J.D., for providing input for the "Bioretention Under Prior Appropriations Water Law" section.

LITERATURE CITED

Barbour, M.G. and W.D. Billings, 2000. North American Terrestrial Vegetation (Second Edition). Cambridge University Press, New York.

Barnett, T.P., R. Malone, W. Pennell, D. Stammer, B. Semtner, and W. Washington, 2004. The Effects of Climate Change on Water Resources in the West: Introduction and Overview. Climate Change 62:1-11.

Barnett, T.P. and D.W. Pierce, 2009. Sustainable Water Deliveries From the Colorado River in a Changing Climate. Proceedings of the National Academy of Science 106(18):7334-7338.

Belnap, J., 1995. Surface Disturbances: Their Role in Accelerating Desertification. Environmental Monitoring and Assessment 37(1-3):39-57.

Brisson, J. and J.F. Reynolds, 1994. The Effect of Neighbors on Root Distribution in a Creotebush (*Larrea tridentata*) Population. Ecology 75:1693-1702.

Brix, H., 1993. Wastewater Treatment in Constructed Wetlands: System Design, Removal Processes, and Treatment Performance. *In*: Constructed Wetlands for Water Quality Improvements, G.A. Moshiri (Editor). Lewis Publishing, Ann Arbor, Michigan, pp. 219-225.

Canadell, J., R.B. Jackson, J.R. Ehlringer, H.A. Mooney, O.E. Sala, and E.D. Schulze, 1996. Maximum Rooting Depth of Vegetation Types at the Global Scale. Oecologia 108:583-595.

Carriquiry, J.D. and A. Sanchez, 1999. Sedimentation in the Colorado River Delta and Upper Gulf of California After Nearly a Century of Discharge Loss. Marine Geology 158(1-4):125-145.

Christensen, N.S. and D.P. Lettenmaier, 2007. A Multimodel Ensemble Approach to Assessment of Climate Change Impacts on the Hydrology and Water Resources of the Colorado River Basin. Hydrology and Earth System Sciences 11:1417-1434.

Claessens, L., C. Hopkins, E. Rastetter, and J. Vallino, 2006. Land Use and Climate Effects of Water Budget. Water Resources Research 42(3):W03426.

Cuevas E., E. Medina, 1986. Nutrient Dynamics Within Amazonian Forest Ecosystems 1. Nutrient Flux in Fine Litter Fall and Efficiency of Nutrient Utilization. Oecologia 68:466-472.

Davis, A.P., W.F. Hunt, R.G. Traver, and M. Clar, 2009. Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3):109-117.

Davis, A.P., S. Shokouhian, H. Sharma, and C. Minami, 2001. Laboratory Study of Biological Retention for Urban Stormwater Management. Water Environment Research 73(1):5-14.

Dietz, M.Z. and J.C. Clausen, 2005. A Field Evaluation of Rain Garden Flow and Pollution Treatment. Water, Air, and Soil Pollution 167:123-138.

Donovan, L.A. and J.R. Ehlringer, 1994. Water Stress and Use of Summer Precipitation in a Great Basin Shrub Community. Functional Ecology 8(3):289-297.

Ehleringer, J.R., S.L. Phillips, W.S.F. Schuester, and D.R. Sanquist, 1991. Differential Utilization of Summer Rains by Desert Plants. Oecologia 88:430-434.

Elfving, D.C., M.R. Kaufmann, and A.E. Hall, 1972. Interpreting Leaf Water Potential Measurements With a Model of the Soil-Plant-Atmosphere Continuum. Physiologia Plantarum 27:161-168.

Emerson, C.H. and R.G. Traver, 2008. Multi-Year and Seasonal Variation of Infiltration From Stormwater Best Management Practice. Journal of Irrigation and Drainage Engineering 134(5):598-605.

Eriksson, E., K. Auffarth, M. Henze, and A. Lendin, 2002. Characteristics of Grey Wastewater. Urban Water 4(1):85-104.

Fernandez, O.A. and M.M. Caldwell, 1975. Phenology and Dynamics of Root Growth of Three Cool Semi-Arid Desert Shrubs Under Field Conditions. Ecology 63:2.

Gianinazzi-Pearson, V., 1996. Plant Cell Response to Arbuscular Mycorrhizal Fungi: Getting to the Roots of the Symbiosis. The Plant Cell 8:1871-1883.

Heady, H.F. and R.D. Child, 1994. Rangeland Ecology and Management. Westview Press, Boulder, Colorado.

Hirschman, D. and J. Kosco, 2008. Managing Stormwater in Your Community: A Guide for Building an Effective Post Construction Program. Center for Watershed Protection. http://www.cwp.org/documents/cat_view/76-stormwater-management-publications.html, *accessed* October, 2008.

Holecheck, J.L., R.D. Piper, and C.H. Herbel, 2004. Range Management: Principles and Practices (Fifth Edition). Prentice-Hall, Upper Saddle River, New Jersey, 607 pp.

Hollis, G.E., 1975. The Effect of Urbanization on Floods of Different Recurrence Interval. Water Resources Research 11(3):431-435.

Houdeshel, C.D., C.A. Pomeroy, L. Hair, and J. Moeller, 2011. Cost Estimating Tools for Low-Impact Development Best Management Practices: Challenges, Limitations and Implications. Journal of Irrigation and Drainage 137(3):183-189.

Hsieh, C. and A.P. Davis, 2005. Evaluation and Optimization of Bioretention Media for Treatment of Urban Stormwater Runoff. Journal of Environmental Engineering 131(11):1521-1531.

Hultine, K.R., R.L. Scott, W.L. Cable, D.C. Goodrich, and D.G. Williams, 2004. Hydraulic Redistribution by a Dominant, Warm-Desert Phreatophyte: Seasonal Patterns and Response to Precipitation Pulses. Functional Ecology 18:530-538.

Hunt, W.F., A. Brown, J.K. McKnett, and J.M. Hathaway, 2010. Bioretention Design: One Size Does Not Fit All. Proceedings of the National Conference of the Stormwater Industry Association, Stormwater, Sydney, Australia.

Hunt, W.F., A.R. Jarrett, J.T. Smith, and L.J. Sharkey, 2006. Evaluating Bioretention Hydrology and Nutrient Removal at Three Filed Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132(6):600-608.

Jackson, R.B., J. Canadell, J.R. Ehleringer, H.A. Mooney, O.E. Sala, and E.D. Schulze, 1996. A Global Analysis of Rooting Distributions for Terrestrial Biomes. Oecologia 108:389-411.

Klinge, H., 1975. Root Mass Estimation in Lowland Tropical Rain Forests of Central Amazonia, Brazil. III. Nutrients in Fine Roots from Giant Humus Pools. Journal of Tropical Ecology 16:28-38.

Knapp, A.K., J.M. Briggs, D.C. Hartnett, and S.L. Collins, 1998. Grassland Dynamics. Oxford University Press, New York City, New York.

Kummerow, J., D. Krause, and W. Jow, 1977. Root Systems of Chaparral Shrubs. Oecologia 29:163-177.

LID-Stormwater.net, 2011. Low Impact Development Urban Stormwater Design Tools Website. http://www.lid-stormwater.net/, *accessed* September 29, 2011.

Linton, M.J., J.S. Sperry, and D.G. Williams, 1998. Limits to Water Transport in *Juniperus osteosperma* and *Pinus edulis*: Implications for Drought Tolerance and Regulation of Transpiration. Functional Ecology 12(6):906-911.

Low Impact Development Center, 2009. Rain Garden Design Templates. http://www.lowimpactdevelopment.org/raingarden_design/index.htm, *accessed* October 2009.

Lucas, W.C. and M. Greenway, 2010. Nitrogen Retention in Bioretention Mesocosms With Outlet Controls. World Environmental and Water Resources Congress 2010: Challenges of Change. Urban Water Resources Research Council – 7th Urban Watershed Management Symposium. Providence, Rhode Island, pp. 3038-3047, doi: 10.1061/41114(371)311.

Mack, R.N., 1981. Invasion of *Bromus tectorum* L. Into Western North America: An Ecological Chronical. Agro-Ecosystems 7:145-165.

MacMahon, J.A., 2000. Warm Desert. *In*: North American Terrestrial Vegetation (Second Edition), M.G. Barbour and W.D. Billings (Editors). Cambridge University Press, New York, pp. 285-322.

Miller, P.M., J.D. Bates, T.J. Svejcar, F.B. Pierson, and L.E. Eddelman, 2005. Biology, Ecology, and Management of Western Juniper. Oregon State University Agricultural Experiment Station Technical Bulletin 152, Corvallis, Oregon.

Miller, P.M., L. E Eddleman, and S. Kramer, 1990. Allocation Patterns of Carbon and Minerals in Juvenile and Small-Adult *Juniperus occidentalis*. Forest Science 36:734-774.

Montague, T. and R. Kjelgren, 2003. Energy Balance of Six Common Landscaping Surfaces and the Influence of Surface Properties on Gas Exchange of Four Containerized Tree Species. Scientia Horticulturae 100:229-249.

Nagaraja, S., 1987. Effects of Soil Texture on the Rooting Pattern of Thompson Seedless Vine on Own Roots and Ramsey Rootstock in Irrigated Vineyards. American Journal of Enology and Viticulture 38(1):54-59.

North Carolina State University, 2011. Bioretetnion at NC State University BAE Design Specifications. http://www.bae.ncsu.edu/topic/bioretention/design.html, *accessed* September 29, 2011.

NRC (National Research Council) Committee on Reducing Stormwater Discharge Contributions to Water Pollution, 2008. Reducing Urban Stormwater Management in the United States. The National Academies Press, Washington, D.C.

Pataki, D.E., R.J. Alig, A.S. Fung, N.E. Golumiewski, C.A. Kennedy, E.G. McPherson, D.J. Nowak, R.V. Pouyat, and P. Romero Lankao, 2006. Urban Ecosystems and the North American Carbon Cycle. Global Change Biology 12:2092-2102.

Pomeroy, C.A. and L.A. Roesner, 2007. Tools for the Evaluation of Stormwater Management Practices That Provide Ecological Stability in Urban Streams. *In*: Cities of the Future: Towards Integrated Sustainable Water and Landscape Management, V. Novotny, L. Breckenridge, and P. Brown (Editors). IWA Publishing, London, United Kingdom, pp. 174-190.

Prince George's County, Maryland PGCo, 1999. The Bioretention Manual. Department of Environmental Resources, Prince George's County, Maryland.

Quinlan, P., 2010. Water: Green Infrastructure Touted Amid New Regulatory, Legislative Push, Published 10/1/2010. http://www.eenews.net/, *accessed* November 15, 2010.

Requena, N., E. Perez-Solis, C. Azcon-Aguilar, P. Jeffries, and J. Barea, 2001. Management of Indigenous Plant-Microbe Symbioses Aids Restoration of Desertified Ecosystems. Applied and Environmental Microbiology 67:495-498.

Richards, J.H. and M.M. Caldwell, 1987. Hydraulic Lift: Substantial Nocturnal Water Transport Between Soil Layers by *Artemisia tridentata* Roots. Oecologia 73:486-489.

Rodin, L.E. and N.I. Bazilevich, 1967. Production and Mineral Cycling in Terrestrial Vegetation. Oliver & Boyd, Edinburgh, 288 pp.

Roesner, L.B., 2001. Are Best Management Practice Criteria Really Environmentally Friendly? Journal of Water Resources Planning and Management 127(3):150-154.

Salt Lake City, Utah, 2010. Water Conservation Information Page. http://www.slcclassic.com/slcgreen/water/conservation.htm, *accessed* October 2010.

Schwinning, S., J. Belnap, D.R. Bowling, and J.R. Ehleringer, 2008. Sensitivity of the Colorado Plateau to Change: Climate, Ecosystems, and Society. Ecology and Society 13(2):28.

Silver, W.L., J. Neff, M. McGroody, E. Veldkamp, M. Keller, and R. Cosme, 2000. Effects of Soil Texture on Below Ground Carbon and Nutrient Storage in a Lowland Amazon Forest Ecosystem. Ecosystems 3:193-209.

Sitler, R. and S. Clark, 2011. Impacts of Bioretention Design of the Calculation Method for the 95th Percentile Rain Event. Proceedings of the World Environment and Water Resources 2011 Congress, Palm Springs, California.

Sperry, J.S., U.G. Hacke, R. Oren, and J.P. Comstock, 2002. Water Deficits and Hydraulic Limits to Leaf Water Supply. Plant, Cell & Environment 25:251-263.

Sperry, J.S., N.M. Holbrook, M.H. Zimmermann, and M.T. Tyree, 1987. Spring Filling of Xylem Vessels in Wild Grapevine. Plant Physiology 83:414-417.

Sperry, J.S. and J.E.M. Sullivan, 1992. Xylem Embolism in Response to Freeze-Thaw Cycles and Water Stress in Ring-Porous, Diffuse-Porous, and Conifer Species. Plant Physiology 100:605-613.

Sperry, J.S. and M.T. Tyree, 1988. Mechanism of Water-Stress Induced Xylem Embolism. Plant Physiology 88:581-587.

Stubbendiek, J., S.L. Hatch, and C.H. Butterfield, 1997. North American Range Plants. University of Nebraska Press. Lincoln, Nebraska.

Tao, L. and Z. Zhiwei, 2005. Arbuscular Mycorrhizas in a Hot and Arid Ecosystem in Southwest China. Applied Soil Ecology 29(2):135-141.

Treseder, K.K. and K.M. Turner, 2007. Glomalin in Ecosystems. Soil Science Society of America Journal 71:1257-1266.

Tyree, M.T. and J.S. Sperry, 1989. Vulnerability of Xylem to Cavitation and Embolism. Annual Review of Plant Physiology and Plant Molecular Biology, 40:19-38.

Tzoulas, K., K. Korpela, S. Venn, V. Yli-Pelkonen, A. Kazmierczak, J. Niemelä, and P. James, 2007. Promoting Ecosystem and Human Health in Urban Areas Using Green Infrastructure: A Literature Review. Landscape and Urban Planning 81:167-178.

Urbonas, B., 2000. Assessment of Stormwater Best Management Practice Effectiveness. *In*: Innovative Urban Wet-Weather Flow Management Systems, R. Field, J.P. Heany, and R. Pitt (Editors). Tehnomic Publishing Company, Lancaster, Michigan, pp. 255-295.

U.S. Census Bureau, Population Division, 2005. Interim State Population Projections. U.S. Census Bureau website: http://www.census.gov/population/www/projections/projectionsagesex.html, *accessed* July 2009.

U.S. Department of Agriculture, 1986. Urban Hydrology for Small Watersheds. Technical Release 55 (TR-55) (Second Edition). Natural Resource Conservation Engineering Division. http://www.cpesc.org/reference/tr55.pdf, *accessed* December 2011.

USDOI (U.S. Department of the Interior); Bureau of Reclamation, 2007. Final Environmental Impact Statement, Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead. http://www.usbr.gov/lc/region/programs/strategies/FEIS/index.html, *accessed* November 2010.

USEPA, 2006. Bioretention (Rain Gardens) Information Sheet. http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=factsheet_results&view=specific&bmp=72&minmeasure=5, *accessed* October 2009.

USEPA, 2009. Federal Stormwater Management Requirements. http://www.epa.gov/greeningepa/stormwater/requirements.htm, *accessed* June 2011.

USEPA, 2010a. National Summary of Impaired Waters and TMDL Information. http://ofmpub.epa.gov/tmdl_waters10/attains_nation_cy.control?p_report_type=T#causes_303d, *accessed* February 2010.

USEPA, 2010b. Green Infrastructure in Arid and Semiarid Climates. http://www.epa.gov/npdes/pubs/arid_climates_casestudy.pdf, *accessed* January 31, 2011.

USEPA, 2011. Proposed National Rulemaking to Strengthen the Stormwater Program. http://cfpub.epa.gov/npdes/stormwater/rulemaking.cfm, *accessed* September 2011.

West, A.G., K.R. Hultine, T.L. Jackson, and J.R. Ehleringer, 2007. Differential Summer Water Use by *Pinus edulis* and *Juniperus osteosperma* Reflects Contrasting Hydraulic Characteristics. Tree Physiology 27:1711-1720.

West, N.E. and J.A. Young, 1990. Vegetation of Intermountain Valleys and Lower Mountain Slopes. *In*: Terrestrial Vegetation of North America (Second Edition), M.G. Barbour and W.D. Billings (Editors). Cambridge University Press, New York.

Whisenant, S.G., 1999. Repairing Damaged Wildlands. Cambridge University Press, Cambridge, United Kingdom.

Wilcox, B.P., D.D. Breshears, and H.J. Turin, 2003. Hydraulic Conductivity in a Pinon-Juniper Woodland: Influence of Vegetation. Soil Science Society of America Journal 67:1243-1249.

Wilcox, B.P., W.J. Rawls, D.L. Brakensiek, and J.R. Write, 1990. Predicting Runoff From Rangeland Catchments: A Comparison of Two Models. Water Resources Research 26(10):2401-2410.

Wilcox, B.P., M. Sbaa, W.H. Blackburn, and J.H. Miligan, 1992. Runoff Prediction From Sagebrush Rangelands Using Water Erosion Prediction Project (WERP) Technology. Journal of Range Management 45:470-474.

Wright, S.F. and A. Upadhyaya, 1996. Extraction of an Abundant and Unusual Protein From Soil and Comparison With Hyphal Protein of Arbuscular Mycorrhizal Fungi. Soil Science 161:575-586.

Zhang, L., E.A. Seagren, A.P. Davis, and J.S. Karns, 2011. Long-Term Sustainability of *Escherichia coli* Removal in Conventional Bioretention Media. Journal of Environmental Engineering 137:669-677.

Zimmermann, M.H., 1983, Xylem Structure and the Ascent of Sap. Springer-Verlag, New York.