AN ABSTRACT OF THE DISSERTATION OF

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Title: Water Efficiency for Urban Landscapes in Semi-Arid Environments

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Urban landscape water use is increasingly a focus of water conservation efforts. This is especially true in the arid and semi-arid regions of the western United States where increased demand, environmental concerns, and extended periods of drought have created chronic water shortages. However, until recently, little attention has been paid to the design and management of water efficient urban landscapes and irrigation systems. Concepts and strategies have often been uncritically translated from the production agriculture context. For example, integrated water use efficiency is broadly defined as biomass production or yield per unit of water consumed via transpiration. In the context of crop irrigation, the definition also sometimes includes the water delivery efficiency of irrigation systems. These definitions can potentially be problematic in urban landscape contexts where plant biomass or yield are not necessarily the functional goals. Instead, traits such as aesthetics and plant health are often more important, but we don't have a good understanding how those traits relate to water use for many types of urban

landscapes. In addition, it is possible that individual management decisions might compromise the target design efficiency of irrigation systems to a much greater degree in urban residential contexts than in production agricultural contexts. In this dissertation, I look at three aspects of outdoor water use in semi-arid urban environments, including results of two separate studies looking at methods of increasing water use efficiency in created landscapes.

Chapter one provides a broad discussion of landscape water use in the context of extended drought conditions in the western United States, and suggests methods to increase conservation through design elements and management practices. I present a summary of landscape industry efforts to increase efficiency in outdoor water use through technological advances, educational programs, and methods to model the water requirement of urban landscapes, but conclude that current efforts may not be sufficient to address the growing need for water conservation in urban landscapes.

In Chapter two, I explore the historic development of urban landscape irrigation and discuss issues related to water availability and allocation that remain persistent and are reflected in current debates over water use. I found that urban landscape irrigation in the western United States developed from the initially agrarian oriented settlement of southern California and efforts to supply water to rapidly growing commercial agriculture in the arid west. Technological advances in water capture, transport and distribution for agricultural production were quickly adopted and modified for use in the expanding urban communities of southern California. The growth of urban demand for water fostered the development of dedicated sources of water and municipal water delivery systems that were distinct from agricultural delivery networks. Urban growth also catalyzed the development of an entire industry focused on urban landscape irrigation. The industry burgeoned after World War II, primarily in response to new materials and technologies developed as part of the war effort, and has experienced exponential growth since that time. Current work to increase irrigation efficiency has shifted from a utilitarian view to reflect more recent concerns about environmental quality, and suggest a subtle change in social values concerning water use. Recent efforts target increasing the efficiency of existing methods, and are generally reflected in a reduction of patent applications for profound technological changes in urban irrigation.

In Chapter three, I assess the correlation between xylem water potential of four xerophyte shrub species and soil moisture levels, reference evapotranspiration (ET_{ref}), and vapor pressure deficit (VPD), and determine the water saving potential of a native plant xeric landscape in an urban setting through evaluation of three common models of determining landscape water demand: Hunter Industries, EPA WaterSense, and SLIDE (Simplified Landscape Irrigation Design Estimator). Each approach relies on reference evapotranspiration (ET_{ref}) as the primary driver of landscape water use but differ in the level of complexity.

I found no statistically significant relationship between xylem water potential and ET_{ref} or VPD, but a strong correlation with soil moisture levels. Despite experiencing periods of extreme water stress, most of the xerophyte species in the study showed no gross morphological signs of water stress, and had positive annual growth. This occurred even though the species where in a highly modified residential landscape.

Results of the evaluation of the scheduling models suggest that while xerophyte species can be successfully used in urban landscapes, the common evapotranspiration based approaches for estimating landscape water needs are inappropriate for landscape types dominated by xerophyte species. In addition, the relationship between plant water status and aesthetic quality varies considerably among species. While some species maintained the same aesthetic quality independent of water stress, others suffered seasonally degraded aesthetic quality as a result of their specific drought response adaptations (i.e. leaf drop). These adaptive responses were reported by the homeowners as degraded aesthetic quality. This may affect the acceptability of reduced irrigation use in semi-arid environments. However, aesthetic value and acceptance of indicators of drought stress in a created landscape is shown to be highly subjective.

Chapter four presents a case study of the modification of an existing commercial landscape irrigation system in a semi-arid urban environment with the goal of achieving a minimum 30% reduction in water use. We found that irrigation water use levels can be significantly reduced in an existing commercial system through careful re-design and the use of currently available irrigation technologies. We achieved a 41% reduction in outdoor water use in one year through modification of an existing irrigation system at a commercial development in a semi-arid environment, but water use was still in excess of recommended application rates. Additionally, maintenance practices are shown to adversely affect the efficient use of water, negating benefits of the retrofit and diminishing the return on investment.

In summary, this dissertation found that modifying plant choice and the design of irrigation systems can improve water use efficiency in semi-arid urban landscapes. However, many of the current management recommendations associated with irrigation scheduling are inappropriately applied to the most xerophytic landscape designs. This partly reflects the agricultural legacy of urban irrigation designs and strategies. In addition, the water efficiency of even the best designs can by severely compromised by inappropriate day-to-day management. This can happen even on a project that was designed to showcase a water efficient design. Developing better management protocols and training that maximize the designed water efficiency of urban landscapes should be a priority.

Water Efficiency for Urban Landscapes in Semi-Arid Environments

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Richard Martinson, Author

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Finally, I’d like to dedicate this work to my Dad, the late Fred Martinson. He would have been proud, and a little surprised, that I took on this endeavor. I hope he’s somehow aware of all this.

CONTRIBUTION OF AUTHORS

Chapter 2. John Lambrinos provided advice, editing, and some of the images for this chapter. Dennis Albert provided editing and enthusiastic feedback on this chapter.

Chapter 3. John Lambrinos provided advice in experimental protocols, editing, feedback, and contributed to statistical analysis in this chapter. Ricardo Mata-Gonzalez provided essential advice on methodology, editing, and review of the text and figures.

Chapter 4. John Lambrinos provided advice and editing of this chapter.

John Lambrinos, Dennis Albert, and Ricardo Mata-Gonzalez provided the primary comments and edits of the entire dissertation.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF APPENDICES

Appendix

LIST OF APPENDIX FIGURES

LIST OF APPENDIX TABLES

Chapter 1 - The Efficiency of Water Use in Urban Landscapes

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Introduction. Water use in the western United States is a complex issue involving social, environmental, and legal facets that have developed over the past two centuries. Water supplies and use have been affected by population growth, economic trends, legal decisions, and periodic droughts since water-use data have been collected (Hutson et al. 2004). Currently, allocation and use of water is becoming alarmingly contentious in response to long-term continued drought and reduced availability throughout the arid and semi-arid environments of the west. The urgency of the issue is being expressed through increased litigation (Doremus and Tarlock 2003, Boehlert and Jaeger 2010) and occasionally violence (Doremus and Tarlock 2008). To address water supply concerns, municipalities and state governments are becoming more explicit in regulations and policies developed to encourage water conservation, often targeting landscape water use as an easily attainable avenue for reducing water use in urban environments. However, the efficacy of programs developed by the irrigation industry and the effectiveness of the practical application of those programs on water conservation have rarely been scrutinized. This dissertation provides a perspective on the usefulness of current water conservation approaches through a review of the historic development of landscape irrigation, and two studies of divergent approaches to increase the efficiency of water use in semi-arid urban landscapes.

Water and the Marketing of California.

Water used to irrigate landscapes accounts for 40-70% of all domestic water used in urban areas in the western United States (Kjelgren, Rupp and Kilgren 2000, Hilaire et al. 2008), but domestic use is frequently referenced as accounting for only 1% of all uses of fresh water in the western U.S. (Bureau of Reclamation 2017). Agricultural irrigation has remained the highest user of fresh water in the U.S., accounting for approximately 63% of water withdrawals across the country (Hutson et al. 2004).

Early development. Water requirements for agricultural production served as the catalyst for early efforts in water transport and delivery, aiding efforts to promote the west as an opportunity to acquire good agricultural land at prices attractive to immigrants (Hittell 1875, Irish 1897). The effort to market the west largely focused on California as an agricultural mecca, and was instrumental in the development and growth of an irrigation industry developing new technologies and methods to increase water supplies for a rapidly expanding mainly agrarian population. The efforts were so successful that in the year 2000, California was identified as one of three states (California, Texas, & Florida) accounting for one-quarter of all water withdrawals in the U.S. (Hutson et al. 2004). As urban and suburban development expanded in the late 19th and early 20th centuries, irrigation methods and technologies developed for California's agricultural expansion were adopted and modified for use in domestic landscapes, possibly expanding from small subsistence gardens to more ornamental landscapes as communities gained affluence.

The growth and expansion of urban irrigation. Irrigation methods and technologies developed in California during the expansion of the state were adopted by newly formed companies such as RainBird and Toro, many of whom are still in operation, and used to expand irrigation markets throughout the west. Popular magazines such as *House and Garden* (first published in 1901) and *Better Homes and Gardens* (first published as *Fruit, Garden and Home* in 1922) encouraged gardening and landscaping, and included advertising from manufacturers of irrigation systems for urban landscapes. However, concerns about the availability and efficient use of water increased as populations grew and urban development expanded to locations away from easy water sources, requiring creativity and sometimes herculean efforts to maintain a constant supply of water to agricultural and urban communities. Concurrently, marketers maintained an image of an abundance of water in the arid environment of southern California. For example, following the completion of the Los Angeles Aqueduct in 1913, developer William Mulholland stated "*There it is. Take it*" after bringing water 200 miles from the Owens Valley to urban residents of Los Angeles.

The irrigation methods developed for urban communities in southern California were designed to support, as California's first State Engineer William Hall recognized "*… the charm of a life amidst a [luxuriant] semi-tropical foliage…*" (Hall 1888). The techniques developed for irrigating southern California were marketed and used throughout the western United States, regardless of regional variation in environmental conditions, vegetation, or soil type. Those same approaches to irrigation design and planning direct current industry efforts to increase the efficiency of irrigation systems in both urban and agricultural systems. But the focus has shifted since World War II to improving the efficiency of techniques and equipment created for agricultural production in southern California, and signals a subtle shift in social values. End users of irrigation technology are becoming increasingly knowledgeable about the need for water conservation and efficiency in application, and are demanding innovations to meet those needs (Brachmann 2015, Dimitri, Effland and Conklin n.d.), not only for water conservation, but in response to growing concerns over environmental quality.

Evapotranspiration as a method of determining water requirement. A primary effort to increase the efficiency in water use was initiated through measuring evapotranspiration (ET) rates in agricultural crops in the late 1930's in California's central valley. Most of the farming areas in California were classified as very arid, arid, or semi-arid, and the availability and use of water for irrigation determined the agricultural potential of the region. The success of technological advances and methodologies in irrigation in California also influenced irrigation design and management for urban landscapes throughout the west. The work of F.J. Veihmeyer of the University of California in 1938, H.F. Blaney & W.D. Criddle (1945), and G.H. Hargreaves (1948) were instrumental in establishing the use of reference ET (ET_o) as the standard for determining agricultural crop irrigation requirements based on environmental factors (Blaney and Criddle 1945, Hargreaves 1948). Following the widespread dissemination of the Hargreaves method of determining water requirements for agricultural crops, ET_o was adopted by the landscape irrigation industry and has since been the standard method for determining water use requirements for urban landscapes throughout the country.

Urban landscape water requirements. More recently, models designed to modify ET_o by a range of site specific factors (K coefficients) explicitly reflecting conditions unique to urban landscapes have been developed to address increasing concerns over long-term drought conditions and water use efficiency. The models represent efforts by manufacturers (e.g. Hunter, Rain Bird), academic institutions (e.g. University of California, Davis), and governmental agencies (e.g. U.S. Environmental Protection Agency) to standardize approaches for determining landscape water requirements. Municipalities often adopt commonly available irrigation scheduling models for use when calculating water use recommendations for landscapes within their jurisdiction. In urban applications, managers generally modify the equations with environmental variables reflecting local conditions or plant type. All models utilize reference ET as the primary factor affecting water use requirements, but differ in the use of coefficients to modify reference ET rates.

Xeric urban landscapes.

Another approach to reduce water consumption in urban landscapes is the use of xerophytic vegetation as the primary vegetation type. Las Vegas, Los Angeles, Phoenix, Santa Fe and other municipalities in the arid west have developed economic incentive programs designed to reduce outdoor water use (Sovocool, Morgan and Bennett 2006, Morris et al. 1997, Olmstead and Stavins 2009, Campbell, Johnson and Larson 2004, Fleming and Hall 2000) and several recommend using native xerophytic vegetation as a primary method of reducing landscape water demand (Hayden 2015). But the use of reference ET rates and crop coefficients to estimate water requirements of xerophytic vegetation has been questioned (Mata-González, McLendon and Martin 2005) and may not be effective in developing irrigation schedules for urban landscapes using native xerophytes.

Studies on potential water savings in urban landscapes.

This dissertation includes two studies designed to quantify the potential water savings in urban landscapes utilizing different methodologies. The first study quantifies physiological response to drought stress in xerophyte species in an urban environment and assesses the correlation between xylem water potential and three environmental variables; ET rate, vapor pressure deficit, and soil moisture. The second study presents results of the modification of an existing irrigation system utilizing currently available technology in a commercial development and quantifies the impact of management decisions and maintenance practices on water saving potential.

Desert Rain.

Chapter three presents a study completed at Desert Rain, a residential compound located in the semi-arid environment of Bend, Oregon and constructed under the Living Futures green building certification program. The study includes four distinct elements: 1) recording xylem water potential of four xerophyte shrub species in a constructed, unirrigated landscape designed to emulate the structural and vegetative components of the historic sagebrush steppe community characteristic of the site prior to urban development; 2) correlating xylem water potential with soil moisture levels, ET rate, and vapor pressure deficit (VPD); 3) quantifying realized water savings through analysis of three common irrigation scheduling models; and 4) qualifying acceptance of characteristics of drought stressed landscapes. In addition, net primary productivity was assessed through nondestructive methods, comparing biomass of mature vegetation in the landscape with destructively sampled nursery stock, and soil density at the study site was compared with soil density in a relatively undisturbed reference community within the same soil class and vegetative association.

Water use efficiency. Water use efficiency is broadly defined in agricultural systems as biomass production per unit of water (Foley et al. 2011) . The term is also variously applied to plant growth, health, and aesthetic value of plants in urban landscapes. However, water use efficiency in urban landscapes is often also defined as relating to irrigation systems and patterns of distribution or application rate. The efficient use of water in created environments, therefore, reflects both the physiological response and growth patterns of landscape plants, and the design and application of systems intended to provide water to constructed landscapes.

The study at Desert Rain was completed to assess the potential for water use reduction of a designed xeric landscape utilizing native xerophyte species in a semi-arid environment.

Physiological adaptation to drought stress was determined through correlating xylem water potential with soil moisture levels at 10cm, 30cm, and 60cm depths. Patterns of stress response, such as more negative xylem potential or expressions of summer deciduous, were compared with cumulative evapotranspiration (ET_{ref}) rates and vapor pressure deficit (VPD) levels to determine degrees of correlation between plant water use and broad environmental variants. I found no correlation between plant water stress and ET_{ref} or VPD, but a strong correlation with moisture levels, most notably at 30cm depth. These results suggest that current ET based irrigation scheduling models may not be appropriate for determining water requirements for semi-arid landscapes using xerophytic vegetation as the primary plant type.

Biomass measurements completed as part of this study quantify the physiological definition of water-use efficiency. Significant biomass production was recorded for all four study species within the first 18 months of growth. Each shrub was installed as one gallon nursery stock with above-ground biomass ranging from 5.1 to 14.1 grams, and exhibited production rates from 400 to 1200 percent. In addition, *Artemisia tridentata*, *Holodiscus microphyllus (*previously *H. dumosus)*, and *Ericameria nauseosa* exhibited no visual indication of drought stress and retained their aesthetic value even as volumetric soil moisture declined below 10%. *Ribes cereum* was the only species demonstrating visual indicators of drought stress through leaf drop, characteristic of summer dormancy as an adaptation to drought, and raising concerns by the property owner over plant health and aesthetic value. The general lack of visual signs of drought stress at Desert Rain reflects unique drought adaptions typical of many desert perennials. These adaptations include modifications such as altered leaf morphology, extensive or deep root systems, and drought dormancy (Chaves, Maraco, & Pereira 2003).

Water savings potential and model analysis. A second goal of this study is to assess the water saving potential of unirrigated urban landscapes using native xerophytic vegetation as the primary plant type. I assessed this through analysis of three common irrigation scheduling models: Hunter Industries' Runtime Calculator, EPA's WaterSense, and University of California's SLIDE (Simplified Landscape Irrigation Demand Estimator). I hypothesized that greater specificity in plant type, environmental variables, and irrigation materials would result in water use recommendations more closely tied to actual water requirements of a created landscape, but found no statistically significant differences between water volume estimation of the three models reviewed (r=1.0). The Hunter model offered the greatest specificity in environmental and materials variables, but resulted in the highest recommended water use requirement. The EPA's WaterSense model included similar options at a detail less robust than the Hunter model, but resulted in the lowest recommended landscape water use requirement. The SLIDE model resulted in volume recommendations between those of Hunter and WaterSense, even though it relied on a single coefficient reflecting broad plant types loosely associated with physiographic regions of California.

The models I tested represent two divergent approaches to determining landscape water demand. A broad, ecoregional approach is utilized by the SLIDE in classification of common landscape species and development of a modifier reflecting professional opinion about plant/water relations in physiographic regions of California. Alternatively, the Hunter and WaterSense models utilize site specific environmental conditions in addition to the type of irrigation and a modifier selected by the software for general plant types (i.e. drought tolerant). Each approach relies on reference evapotranspiration as the primary driver of landscape water use but differs in the level of complexity. In addition, the SLIDE model recommends modifying reference evapotranspiration by estimated water use requirements of individual species, although the method of determining the average coefficient of all plants in a landscape is unclear. The Hunter and EPA models depend on professional judgement to determine general water requirements of each irrigation zone in a landscape, and use corresponding coefficients and irrigation type and efficiency to calculate water requirement by area. Results from the Hunter model include irrigation scheduling recommendations based on local environmental conditions and water use requirements of each landscape zone. WaterSense and SLIDE quantify recommended water use, but do not include detailed scheduling.

Realized water savings ranged from 17,742 L/ 93m^2 (EPA WaterSense) to 29,606 L/ 93m^2 (Hunter Runtime Calculator), based on 1983 – 2015 historic ET rates, although the realized savings reflect the percent reduction in recommended water use. For example, the EPA WaterSense model resulted in the lowest water use recommendations of the three models tested (79% below ET_{ref}), therefore the realized water savings is the lowest of all models.

Aesthetic value. Many urban centers in the western United States are in ecoregions (Omernik 2004) that experience generally low or markedly seasonal patterns of precipitation that create prolonged periods of soil water deficit during the year. As a result, most urban landscapes in the region use seasonal irrigation to maintain plant health and aesthetic quality, although the subjective nature of aesthetic quality is well documented (Thompson 2000, Thorne and Huang 1991, Tyrväinen, Silvennoinen and Kolehmainen 2003).

In this study, I qualitatively assessed plant health and aesthetic quality by direct visual assessment and informal interviews with the homeowners twice a month to record perceived landscape health and visual quality. At Desert Rain, three of the four study species, *A. tridentata*, *H. microphyllus* and *E. nauseosa* did not exhibit visual indicators of drought stress and retained their aesthetic value throughout the growing season, even as volumetric soil moisture declined below 10%. In contrast, *R. cereum* dropped most of its leaves in late summer and displayed signs characteristic of a summer deciduous strategy for surviving drought. Generally, the homeowners were very pleased with the visual quality and apparent health of the landscape, and the rapid growth of the plants. They did express concern about the visual stress of the *Ribes* in August and continued their concern through September.

I also completed an informal survey of homeowners to determine the general level of acceptance of characteristics of drought stressed landscapes and found similar responses to indicators of drought stress (Figure 1.1).

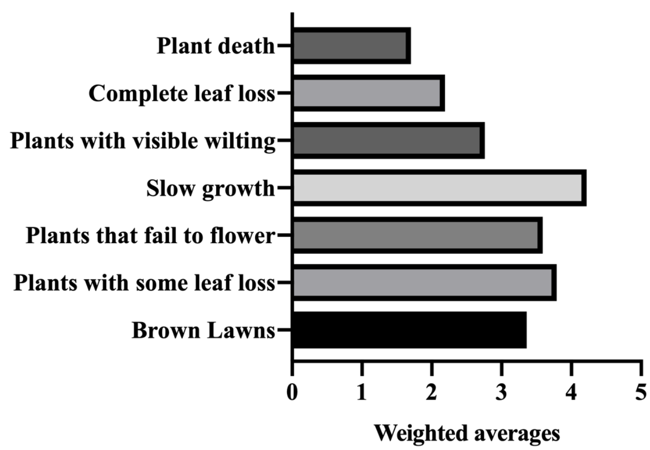

Figure 1.1: Weighted averages of reported tolerance of indicators of drought stress in urban landscapes. (N=194). Responses were rated 1-5 on a scale of tolerance: Not at all tolerant = 1, Minimally tolerant = 2, Neutral =3, Somewhat tolerant =4, Very tolerant =5. Results indicate greater tolerance for drought responses not affecting the visual quality of individual plants. A notable exception is lawns. The degree of acceptance of brown lawns may be a result of educational efforts by municipalities focusing on lawns as high water use landscape elements.

Generally, respondents were more accepting of drought stress characteristics that did not affect the visual quality of landscape plants. However, 66.84% of respondents were somewhat tolerant or very tolerant of some leaf loss (N=194), but only 20.53% of respondents were tolerant of complete leaf loss. Similarly, 34.74% of respondents expressed tolerance of visible wilting, and only 7.85% were tolerant of plant death as a response to drought stress.

Summit Park.

The second study presents results of the modification of an existing irrigation system utilizing currently available technology at Summit Park, a low-income housing complex covering approximately 2.1 ha in Bend, Oregon, a city of ~80,000 at 1,115 m elevation. The retrofit process involved a detailed irrigation audit and subsequent design modifications to both the irrigation system and landscape plant composition, approaches that are commonly promoted as water conservation strategies. This provided a unique opportunity to study the effectiveness of these strategies at reducing landscape water use in a semi-arid urban environment. I also assess the effect of management decisions on water use patterns over two years following retrofit of the irrigation system.

Site description. Summit Park is a public-private partnership. The city of Bend maintains ownership of the land and subsidizes a portion of the rent residents pay. A private developer owns the structures and manages the property for low-income residents (Bend 2015). The complex was originally constructed in the mid 1990's and includes 7568 m^2 of irrigated area: 6556 m^2 of turf and 1012 m^2 of planted shrub beds (Bend 2016). Sod covers most of the property outside the buildings. A one meter tall berm planted with a mix of conifer and deciduous shrub and tree species runs the length of the east side of the property. Two large berms (>2 meters tall) run north-south in a common area between two multi-unit buildings, and narrow planting beds with mature conifer shrubs exist along the foundation of each building that faces the parking area. The plantings on each side of the entry drive are predominantly lawn with planting beds of aspen

(*Populus tremuloides*), redtwig dogwood (*Cornus sericeus*), barberry (*Berberis sp*.) and Oregon grape (*Mahonia aquifolium*). Sod composition on site consists of three grass species; *Lolium perenne, Poa pratensis,* and *Festuca spp* (Baker et al. 2014). Shrub beds are limited to small linear plantings between sidewalks and building foundations.

Outdoor water at the site is uniquely metered separately from indoor use, providing detailed landscape water use data on a weekly basis. These data exist for the years 2011-2018 covering a period both before and after project implementation in 2015. Records provided by the city document a mean annual application rate over the five years prior to the implementation of this project (2011-2015) of 11.7 x 10^6 liters (Bend 2016).

Separate metering of outdoor water use is rare in the city of Bend. The city-collected data on long-term trends in landscape water use at Summit Park provided a unique opportunity to quantify the effects of irrigation system alteration.

Project participants and goals. This project was initiated by the building owners as a way of reducing operating costs at Summit Park, primarily through a reduction of outdoor water use. The city supported the project by providing partial project funding, supplying water use data, and monitoring results. I provided planning, design, and implementation of the project as an opportunity to study results of the retrofit of an existing irrigation system.

The property owners identified a target reduction of 30% below annual outdoor water use, primarily in response to results of the 2013 audit which documented excessive water use, but also in reply to city pressure to reduce outdoor water use. The initial vision for achieving this goal involved improving the efficiency of the irrigation system and converting a significant proportion of the landscape from relatively high water use vegetation to a low water use types modeled on local high desert plant communities. However, as I describe below, budget constraints forced modifications to the original design concept. The final plan was designed to achieve the majority of target water use reductions through improvements in irrigation system efficiency, although replacement of high water use plants with native xerophytic species was completed for approximately 10% of the site. Additionally, modifications to site topography were incorporated in an effort to retain more stormwater on site. The project included four distinct steps: 1) an irrigation audit, 2) review of audit results and retrofit design development, 3) design implementation, and 4) monitoring.

Irrigation audit. The irrigation audit identified 18 separate irrigation zones, 17 of which were functional. Each zone contained a variety of irrigation heads, nozzle sizes, and precipitation rates. Thirteen zones were identified as irrigating turf, two were identified as shrub zones, and three were mixed turf and shrub beds. The audit also showed that the system was not a unified design. System elements were inconsistent and included a mixture of different irrigation head types, nozzle types and sizes, as well as redundancies in head placement. The existing sprinkler heads were also of older relatively less efficient designs. In addition, the system had several broken or leaking irrigation control valves. The system appeared to have been modified over time, with multiple heads irrigating the same area on multiple schedules, and a variety of head types by different manufacturers installed on the same irrigation zone.

The rate of water delivery varied considerably both across zones as well as within zones across scheduled irrigation run times (Figure 1.2). This spatial and temporal heterogeneity in water application rate was a significant source of system inefficiency. Calculations completed as part of the audit indicated that replacing sprinkler bodies and heads with a uniform more efficient head design would result in an expected 51% decrease in total annual water use at Summit Park.

Retrofit design. The system retrofit focused on three primary areas: 1) improving the irrigation precipitation rate and distribution uniformity through standardizing nozzle types, updating to more efficient irrigation head designs, and improving the spatial patterning of irrigation heads; 2) addressing grading concerns and improving onsite storm water retention; 3) replacing some of the high water use vegetation with native xerophytic species. Budget constraints were a significant consideration in the design process. These constraints shaped the project design in two significant ways. First, to affect the most change within budget constraints, the existing irrigation zones were prioritized in terms of their inefficiency. Only zones that were identified as exceeding a mean precipitation rate over 2.54 cm per hour were retrofitted (Figure 1.2). Secondly, early designs called for replacing 90% of the existing vegetation with xerophytic native species. However, budget constraints forced most of these plans to be scrapped. Instead, only about 10% of the site was replaced with xerophytic species. These were included as part of the stormwater management aspect of the design.

We reviewed precipitation rate data for each head in each of the priority zones and recommended changes in irrigation body type, nozzle size, or head location to increase application efficiency. Consistency in spatial coverage was addressed through adjusting irrigation head placement or removing redundant or ineffective heads. Irrigation precipitation rates were made more temporally uniform by using consistent head and nozzle designs throughout the system. The variation in water pressure inherent in long irrigation runs was mitigated through the use of pressure regulating irrigation bodies.

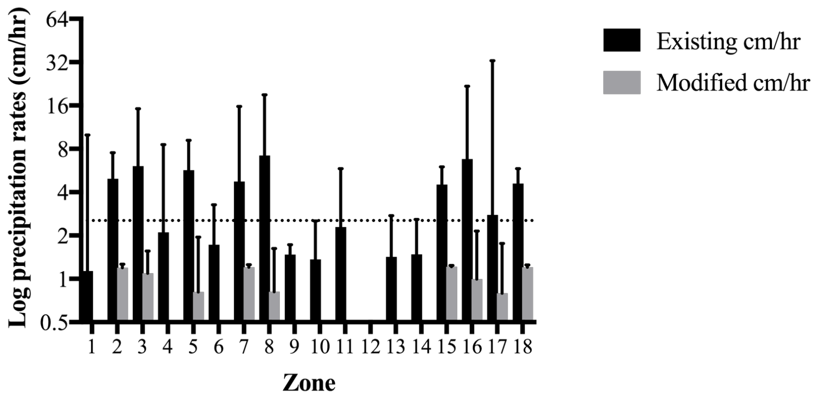

Figure 1.2: Mean precipitation rates recorded for each zone in 2015. To address budget concerns, recommendations for system modification were implemented for each zone with a mean rate exceeding 2.54 cm per hour (dotted line). Dark bars represent the mean precipitation rate before modification; lighter bars indicate precipitation rates following system modification.

Results.

In 2016, the year after the retrofit was implemented, annual irrigation water use was 38.0% less than in pre-retrofit 2015. Over the first three years' post-retrofit annual irrigation water use was an average 34.4% less than the average over the previous three years before implementation (Figure 1.3). This reduction met the benchmark goal of a 30% reduction in outdoor water use. However, it fell short of the anticipated 51% reduction in average water use predicted to occur as a result of the system design changes.

The failure to meet the designed system potential appears to have been largely related to the manual aspects of irrigation scheduling. Detailed weekly water use records for 2018 indicate that irrigation scheduling was not adjusted to account for seasonal changes in water demand. Instead, the system was turned on at the start of spring and set to levels reflecting peak summer water demand. There was other less understandable variation in year to year water use. Irrigated water use at the site had declined in the previous two years (2014, 2015) prior to the implementation of the retrofit. The reason for this is not clear, but it intriguingly occurred after a formal irrigation audit was conducted in 2013. Overall, the year to year variation in water use does not correspond to the yearly variation in estimated water demand reflected in ET_{ref} rates (Figure 1.3). This suggests that manual alterations to irrigation scheduling were not accurately reflecting landscape water needs. We do not have an explanation for the precipitous drop in irrigation water use reported in 2012. It could reflect management decisions, but monitoring equipment error is also a possibility.

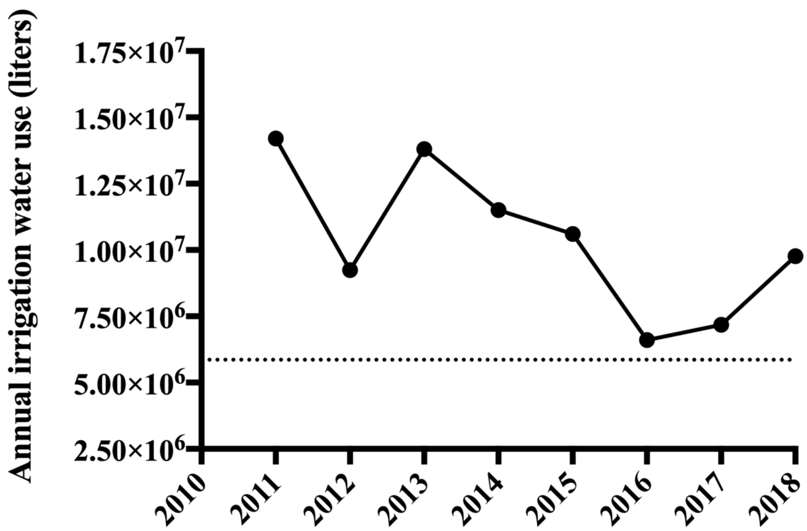

Figure 1.3: Annual water use at Summit Park, Bend Oregon. Our retrofit was completed in the fall of 2015, resulting in a 38% decrease in water use relative to 2015. No environmental explanation for the 2012 decrease in applied volume was identified in AgriMet records. The reduction may be due to a change in irrigation scheduling or management activities, or simply reflect recording error. Increases in water use for 2017 and 2018 reflect landscape management and irrigation scheduling by the landscape maintenance company at Summit Park. Source: City of Bend Public Works 2018.

Discussion.

The Summit Park project was designed to achieve a minimum reduction of 30% in seasonal outdoor water use. We exceeded expectations by achieving a 44% reduction from the 2011-2015 mean documented by the City of Bend. Although the project included some small modifications to the landscape plant composition and topography, the majority of these water use savings were achieved through improving the functional efficiency of the existing irrigation system. The retrofitted system delivered water more uniformly in space and time and at rates that improved water infiltration into the soil. Models and experimental studies indicate that uniformity and application rate are two of the most important factors influencing the application efficiency of landscape irrigation systems (Hilaire et al. 2008). There is considerable evidence that the majority of existing residential irrigation systems have fair to poor spatial uniformity (H. Solomon et al. 2006)

Management. The decision to improve water use efficiency is frequently made by owners or managers who are responsible for fiscal oversight but who have little experience or knowledge about how best to implement changes in ways that will reduce water use but that sustainably maintains the functional goals they have for their landscape. They also lack the capacity to monitor and adaptively manage the system. Professional landscape maintenance contractors could help fill this knowledge gap by properly implementing plans, maintaining systems, and providing active troubleshooting and decision management. However, many landscape management companies have little or no incentive to monitor use or to provide expert water management support. This gap between intent and implementation is a substantial barrier to addressing long-term water use concerns in managed landscapes. But there are no easy solutions. Companies providing landscape maintenance at Summit Park have changed three times since 2015 (Wooden 2018). The lack of consistency in maintenance contributed to the significant variation in water use documented at Summit Park in 2012 (Figure 4). Although the city has an active program in “waterwise” landscaping, involvement in that program is voluntary and the adoption of recommendations developed through the program by landscape maintenance companies is unknown (Buettner 2018). The responsibility to educate maintenance companies on current water use issues and irrigation scheduling is often left to homeowners or property managers.

In their defense, landscape maintenance companies are expected to preserve a level of aesthetic value critically important in urban landscapes (Hayden 2015), and reducing water use often generates questions of aesthetic value. Although aesthetics is a subjective value (Thompson 2000, Thorne and Huang 1991, Tyrväinen et al. 2003), the appearance of a healthy landscape is the primary goal of most landscape maintenance companies. Maintenance practices designed to meet that goal often include the application of water at rates exceeding plant physiological requirements (Martinson, Lambrinos and Mata-Gonzalez In-Press), or base irrigation schedules on experience or intuition (Harris et al. 2012) and fail to consider the effect on long-term water conservation objectives.

For example, my survey on tolerance of characteristics of drought stress in urban landscapes shows that of 176 respondents, 25% decided to irrigate when plants looked stressed, and 22.16% based their irrigation schedule on advice from nursery or landscape professionals. But when asked how to determine the quantity of irrigation to apply, 39.43% of respondents stated they "guess" or go by "gut feeling" (N=175). Water quantity based on advice from landscape professionals was reported as the primary method of determining irrigation schedule by 22.29% of respondents, followed by irrigating until no indications of drought stress were visible (21.14%).

The modification of the irrigation system at Summit Park documents the potential for increasing irrigation efficiency and reducing water use through careful design and application of existing technology. However, maintenance practices have the potential to significantly affect the degree of success in efforts to reduce landscape water use, identifying a need for consistency in educational opportunities for landscape contractors and maintenance companies. The development of educational programs targeting outdoor water use reduction in response to growing concerns over long-term drought and water availability in the western United States must address regional environmental conditions, be responsive to local values, and be collaborative between municipalities, the landscape industry, and educational institutions.

Chapter 2 - A Brief History of Urban Irrigation in the Western United States

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Abstract. The history of irrigation development in the western United States is a complex story of religious freedom, innovation, marketing, social values, and the search for prosperity. Settlement in the west was largely dependent on the availability of water, and the allocation and use of water physically shaped the social and environmental landscape throughout the region. The agricultural settlement of arid lands in California necessitated new approaches to ensure consistency in water availability and allocation for a growing population. Urban developments in southern California during the 19th century adopted and modified irrigation techniques designed for agricultural irrigation in the western U.S. for use in residential landscapes. Continued ingenuity facilitated improvement of irrigation technologies in response to market demand as new materials were developed and made available. This narrative presents a brief history of the evolution of landscape irrigation in southern California, specifically Los Angeles, drawn from historic documents, photographs, patents, and other sources.

Key Words: Urban Landscapes, Irrigation, History, California

Introduction

Irrigation for urban landscapes accounts for 40 – 70% of domestic water use in the western United States (Kjelgren et al. 2000, St. Hilaire et al. 2008). The highest percentage is associated with created landscapes in arid or semi-arid environments common in the western U.S. where water availability, allocation, and use are continuously debated. In response, municipal efforts to reduce water use often view landscape irrigation as an easy target for water conservation efforts in the western United States. Frequent and recurring drought increase concerns over this limited resource and have led to protracted legal disputes and sometimes physical conflict.

The historic development of irrigation in urban and suburban landscapes is a topic missing in the published literature. Work that has been completed generally concentrates on the historical development of regional water storage and supply systems, the development of agricultural use and delivery systems, or the evolution of the legal structure of water rights and allocation. In this review, we provide a historic perspective on the development and growth of urban landscape irrigation in the semi-arid environment of the American west. The State of California figures prominently in this history, and provides the context for the rest of the western United States.

This study is not intended as a comprehensive history of western irrigation, but rather a first broad attempt to outline the key developments in urban irrigation in the west. We also seek to connect this development to broader social, political, and economic changes over the last two centuries. We developed this history from information gleaned through research of historic documents, records, photos, reports, and other sources. Additional research is necessary to substantiate and expand on some of the assumptions and conclusions made here.

We found no existing studies explicitly addressing the history of urban irrigation during our extensive literature search. However, several studies on the history of agricultural irrigation have been written, including discussions on the diffusion of knowledge through settlement patterns (Harper 1974), the adoption of irrigation techniques from indigenous cultures (Tanji and Keyes Jr 2002, Caswell 1991), the influence of technological development (Mercer and Morgan 1991), and the effect of early settlement on development of regional irrigation techniques (Harper 1974, Masters 2015, Warner 1992).

We use this agricultural focused literature as the starting point for our exploration of urban irrigation development. We infer how agricultural designs and practices were transferred to urban settings by examining historic descriptions of irrigation systems, photographs of early urban landscape designs, patents on irrigation technologies, advertisements, and a range of other published materials that document the expansion of urban irrigation in the western U.S

Early Colonial Period

As European colonists settled in the western United States they developed water storage and delivery systems to support their populations. The systems provided irrigation water for crops as well as drinking water for livestock and humans. The design of these systems undoubtedly reflected the colonists own cultural history of agricultural methods learned from the indigenous people of the region, and ad hoc adaptations to their new environment. However, the specific sources of knowledge to construct these early irrigation systems are not well known. Some studies suggest that early colonial technologies were based on historic Spanish irrigation systems (Glick 1972, Harper 1974), but there is also evidence that they were a modification of indigenous irrigation designs (Hutchins 1928), such as the classic Hohokam examples from Arizona (Figure 2.1). It is clear that early Spanish colonists noted the irrigation technologies of the indigenous pueblo cultures of the southwest. For example, records from the Francisco Vázquez de Coronado expedition in 1540 referred to irrigation ditches supplying water to pueblos in Arizona and New Mexico (Hutchins 1928).

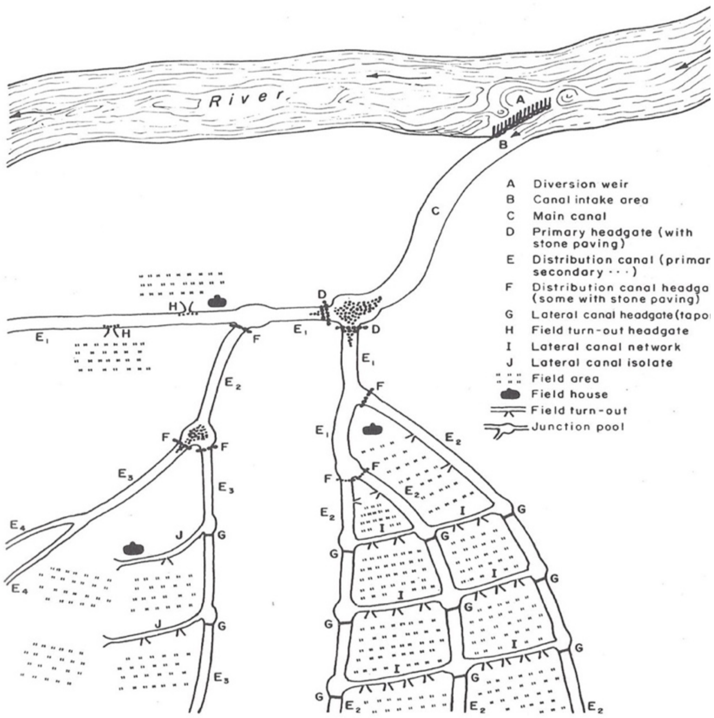

Figure 2.1: Schematic representation of the major components of Hohokam irrigation. The system includes diversion weirs, main canals, lateral canals, distribution ditches, headgates, and bank stabilization; features still used in modern ditch irrigation systems. From Masse, 1991 (used by permission).

The success of the Spanish mission system in the West depended heavily on irrigation, as well as the indigenous labor needed to build and maintain the water storage and delivery systems. One of the oldest preserved irrigation systems in the United States is from Mission Espada along the San Antonio River in Texas (Figure 2.2). This complex includes an aqueduct and dam built in 1731 and a 25 km long Acequia Madre (mother ditch) that irrigated about 1,420 ha of crop land (Tanji and Keyes Jr 2002). Similar canal systems were used in Franciscan missions from Baja California to Point Reyes (Figure 2.3).

Maintenance of the missions was a continual problem for early Franciscans (Priestley

1920), and the establishment of irrigated crops was critical to the development of the mission system. Given that the mission water systems were overseen by Spanish Franciscans and built by indigenous labor it seems plausible that the designs reflected both Spanish and indigenous irrigation techniques. Early water systems in other parts of the Spanish North America such as the Sacramento Valley were likely also a blend of Spanish influences and native techniques, although the influence of Spanish methods on agricultural systems in central California has been disputed (Hess 1912).

Figure 2.2: The Espada Acequia (Espada Aqueduct) built by Franciscan friars in 1731 to provide irrigation water to Mission San Francisco de la Espada in present day San Antonio, Texas USA. Source: Library of Congress, Prints & Photographs Division.

In parts of the west not under strong Spanish influence such as the Pacific Northwest (Oregon, Washington, Idaho) the source of early irrigation technology is even less clear. Although European settlers could grow crops without irrigation in some parts of the region, irrigation systems were a requirement for settlement east of the Cascades. "*Old canals and fruit trees*" irrigated from the Yakima River were noted when the Northern Pacific Railroad was built through Union Gap (near present day Yakima, Washington) in 1884, and "*according to the Indians*" were planted and irrigated prior to the treaty of 1855 (Boening 1918). An earlier record of irrigation ditches and flood irrigation at the Whitman mission near present day Walla Walla, Washington is presented by Boening (1918). The settlers of the region were largely of northern European ancestry, and many presumably lacked practical knowledge of irrigation systems developed in the Mediterranean climate zone of southern Europe. In addition, local Indian tribes were not reported to be practicing irrigation. Although the source of knowledge on irrigation techniques for northwest settlers is undocumented, several sources are plausible: 1) missionaries practiced irrigation before migrating west and brought the knowledge with them, 2) irrigation was observed while migrating west and methods and technology were adopted and later used at settlements, or 3) irrigation was practiced by local tribes and their methods adopted by the missionaries.

Figure 2.3: Irrigation ditch at Mission San Antonio de Padua, near Jolon, California USA. Established in 1771, the Mission moved to its present location in 1773 due to an unstable water source. Source: Christine Delsol, (used by permission)

Despite their murky origins, most of the early irrigation systems in the West were based on a similarly simple design. A network of trenches, canals, and ditches directed water from a stream or river onto agricultural fields, a method known as flood irrigation. This was the most common irrigation technique in the nineteenth century. The approach mostly requires labor to create and maintain the intricate network of channels, not specialized skills or equipment. Variants of this system were employed both by the more organized pueblo and mission communities, as well as homesteaders. Indeed, subsistence farming in semi-arid areas of the western United States would have been difficult without irrigation, and moving water from rivers or streams was the easiest and most economical method of watering crops or small gardens (Vorster 1992, Boening 1918, Tanji and Keyes Jr 2002).

At first, water systems were designed to irrigate relatively small, largely subsistence fields surrounding small settlements. They also provided drinking water and often served a municipal waste function, although these other functions are usually not explicitly highlighted in early descriptions. However, the synonymy between municipal and agricultural water delivery systems began to erode as commercial and commodity focused agriculture replaced subsistence agriculture communities. Farmers began to design dedicated water delivery systems for their fields, and the size of irrigated plots began to grow. In 1844, John Fremont noted irrigation ditches around Captain Sutter's "*extensive wheat fields*" in the Sacramento Valley, a number of girls "*busily engaged in constantly watering the gardens*", and preparations to irrigate his [Sutter's] lands "*by means of the Rio de los Americanos*." (Fremont 1845). Fremont also reports that Mr. Sutter had sown, "*altogether by Indian labor*," three hundred *fanagas* of wheat (1070 ha) that year; a substantial area to be flood irrigated.

Water and development

At the start of the 19th century residential water use was not clearly distinct from agricultural water use. Strictly ornamental plantings were rare and family garden plots were often simply the part of the agricultural field closest to the house. For much of the century government policy and technological innovation remained largely focused on delivering irrigation water and providing flood control to aid crop production. The West, particularly California, was seen as having vast untapped agricultural potential. In 1874, California had a population of only about five hundred thousand, with sixty-five million acres of land suitable for cultivation, but less than two million of it in production (Hittell 1875). The expected expansion of the Southern Pacific Railroad between San Francisco and Seattle promised to open new markets for agricultural goods grown in the central California valley. However, as the West became more fully integrated with the expanding U.S. economy there was growing concern that the availability of water would constrain economic growth. There was even concern that the West had already reached its human capacity: "*In Western America* [defined as west of the 100th meridian]*, there is room for sixty millions more people, who can sustain themselves without encroaching upon any acre now occupied, or upon any property right now vested in individual or corporation*." (1894). A range of private and public efforts where launched to increase water storage capacity, improve flood control, expand water delivery systems and improve the efficiency of irrigation systems. Many of these activities were promoted and coordinated by Irrigation Congress, a quasi-governmental body made up of business owners and state representatives from throughout the western U.S. established in 1891. The 1893 Congress, held in Denver Colorado, described settlement of the west as critically dependent on the availability of water. "*…the future of all the West is bound up in the future of irrigation*" (National Irrigation Congress 1894)

These concerns never managed to make it into real estate advertisements or the economic boosterism of politicians. The West, particularly California, was promoted as a Land of Promise where "*wealth from her soil and sunshine will cure unthrift, bad judgement, and lack of faculty, or make the do-less a doer*" (Irish 1897). California could make every immigrant prosperous. The western U.S. was promoted as an opportunity to acquire good agricultural land that could produce yields greater than were typical in eastern states at prices attractive to migrants (Hittell 1875, Irish 1897).

Although almost every parcel of land was sold as being agriculturally productive, annual rainfall in many areas made dryland farming a marginal to near impossible proposition. Many regions such as southern California also suffered from cyclical droughts, while other areas suffered from seasonal floods. Seasonal flooding in the Sacramento Valley and the rest of the Great Central Valley of California affected the ability to produce market crops (Hittell 1875). It became clear that the management and allocation of water supply was a prerequisite for future development (McAdie, Pardee and Sterling 1905).

Consequently, water strongly influenced patterns of population growth and settlement throughout the 19th century. It forced newly arriving settlers to homestead near existing Spanish acequias or on parcels that real estate companies had connected to newly build private water systems. Misleading advertising could only go so far, and acquiring and distributing water became integral parts of real estate and land development reflected in names such as the *Lankershim Ranch Land and Water Company*. Developers such as the Southern Pacific Railroad and the California Development Company negotiated water rights for the properties they actively marketed to buyers in the east (Schuyler, 1906), a region that was still recovering from "The Long Depression", a severe economic downturn in Europe and the United States from 1873 to

1879 (Bernstein, 1956; Klitgaard & Narron, 2016). Land development companies sometimes went to great lengths to acquire water for parcels. For example, the California Development Company (based in Denver, Colorado) formed a corporation under the laws of the Republic of Mexico called *La Sociodad de Irrigacion y Terrenos do la Baja California*. The company established offices in Mexico City and Los Angeles, acquiring the right to divert water from the Colorado River in Mexican territory "*to the extent of 10,000 cubic feet per second*" and to deliver half of it across the boundary into the United States (Schuyler 1906). The first canal built by the corporation diverted water "*from the natural drainage lines*" to the Alamo River and the Salton Sink.

At least as portrayed in the promotional materials, western development in the 19th century was based on the agrarian Jeffersonian ideal that had influenced the pattern of European settlement in the rest of the United States. However, the dependence of settlements on water storage and delivery systems significantly altered this ideal. The geography of water allowed a relatively few strategically placed landowners to have disproportionate access to and control of water resources. In addition, the costs of building and maintaining water delivery systems created significant economies of scale. Both of these forces favored consolidation and large farm sizes before other social-economic forces did the same elsewhere in the United States (Olmstead and Rhode 2017). At the same time, developers began to market increasingly subdivided parcels where a few acres of high value crops such as fruit trees could be grown. For instance, in the 1890's the Lankershim Ranch Land and Water Company offered 2.5-40 acre parcels in the San Fernando Valley that were then "10 miles from Los Angeles" that could produce an abundance of high value crops (Figure 2.4). The advertising brochure promised "*Ten acres of these lands in bearing fruits will produce a better income than a 160-acre farm East of the Rocky Mountains*"

(Lankershim Ranch Land and Water Co. 1887). Two divergent water systems began to emerge in the late 19th century: One devoted to serving large holder, labor intensive, irrigated agriculture, the other devoted to serving growing urban populations, often on small idealized homestead plots.

Figure 2.4: A map of parcels held by the Lankershim Ranch Land and Water Company in 1887. The holdings were subdivided out of the southern portion of Mission San Fernando Rey de España. Although the parcels where not originally connected to irrigation systems, the company advertised their location within the alluvial floodplains of the Pacoima and Los Angeles rivers as being supplied by "natural subirrigation". https://commons.wikimedia.org/wiki/File:Lankershim_Ranch_Land_and_Water_Company_1887.png

The emergence of urban irrigation

The development of water systems explicitly designed to meet the needs of urban residents accelerated as non-farmer immigrants began to pour into the West. The discovery of gold at Sutter's Mill near Sacramento, California in 1848, and the ensuing Gold Rush (1848-1855) stimulated rapid population growth. Cities and towns were chartered, a state constitutional convention was convened, a state constitution drafted, elections held, and representatives sent to Washington D.C. to lobby for the admission of California as a state (Starr 2005). Between 1847 and 1870, the population of San Francisco grew from 500 to 150,000 (U.S. Bureau of the Census 1870) (Figures 2.5 – 2.6).

As immigration expanded, settlement choices were largely based on climate, water, and access to transportation (Borchert, 1967). Many communities and neighborhoods in California grew around historic missions and utilized the Spanish *acquia* system to provide both domestic and irrigation water (Water and Power Associates, n.d.). However, the expansion of railways and street cars in the west allowed people to settle land that wasn't adjacent to established irrigation supplies (Borchert 1967), stimulating development of settlements with new water supply challenges.

John Wesley Powell's 1879 *Report on the Lands of the Arid Region* argued that irrigation should be considered in settlement patterns in which residents could benefit from the opportunities granted by the control of water: "*…that the inhabitants of these districts may have the benefits of the local social organizations of civilization – such as schools, churches, etc.*" "*…it is essential that the residences should be grouped to the greatest extent possible.*" (Powell 1879). The resulting grouped residences (suburbs) were touted as morally, socially, and aesthetically more appealing than life in the city (D. Schuyler, 1982). During the same period California was being marketed mainly for its agricultural potential and natural beauty rather than it's rapidly growing urban centers (Hittell 1875). But water continued to be a limiting resource affecting settlement patterns and land prices throughout California, and the development of infrastructure ensuring a long-term supply of water was seen as critical to the continued settlement of the west (National Irrigation Congress 1894).

Figure 2.5: Portsmouth Square. Near the San Francisco harbor, 1851. Unknown - Library of Congress Public Domain CALL NUMBER: DAG no. 1331. Created June 1851.

Figure 2.6: San Francisco circa 1870. Roy D. Graves Pictorial Collection Series 1: San Francisco Views. UC Berkeley, Bancroft Library.

The growing power and influence that urban centers had over how the water infrastructure of the West developed is perhaps most exemplified by the completion of the Los Angeles Aqueduct in 1913. The project funded primarily by a bond approved by the residents of Los Angeles brought water to the city from the Owens Valley 200 miles away. The project's chief engineer William Mulholland famously made it clear that city residents would decide how to use the water: "*There it is. Take it*." Just what early city residents did with that water is not clear, but a good many of them did use a portion for landscape irrigation.

There was a burgeoning interest in gardens, gardening, and home horticulture in both Europe and America during the 19th and early 20th centuries (Lyon-Jenness 2004). Publications encouraged the art of landscaping, or "*laying out, planting, and keeping decorated grounds*" as a social value in suburban communities (Scott 1870), and increased marketing of innovations promising to simplify life encouraged the development of neighborhoods outside city cores. In many cases landscaping was used to project affluence...or at least the appearance of it. This was particularly the case in the West where diverse and luxurious landscapes were dependent on irrigation. Photos from the late 19th century indicate that private residences were accessing water for landscape use and appear to be utilizing flood irrigation techniques for large lawns, emulating structures and methods used in agricultural production (Figures 2.7-2.8). It is difficult to evaluate how widespread these practices were, or what their impact was on overall water consumption patterns. In 1911, the average water consumption of Los Angeles residents was 110 gallons per person per day (Board of Public Services Commissioners, 1911), remarkably similar to the 113 gallons per person per day residents used in 2014 (Los Angeles Department of Water and Power) However average per capita water use of city residents has declined since the late 1960's partly as a result of a range of conservations efforts, some which have been focused on landscape irrigation and plant choice. The water use reported in 1911 is also considerably less than current usage in areas that are intensively landscaped with relatively water intensive plants. Usage in these areas can exceed 300 gallons per person per day (California State Water Resources Control Board).

Figure 2.7: Los Angeles residence, circa 1890. Note the expanse of lawns and the water filled zanja (ditch) along the front of the properties. Source: Historical Photo Collection of the Department of Water and Power, City of Los Angeles.

Government officials and civic leaders also saw the social value of landscaping. In 1888, California's first State Engineer William Hall recognized "*…the charm of a life amidst a semi-tropical foliage which irrigation there supports in luxuriance…*". Cities such as San Francisco and Los Angeles used municipal water to irrigate a network of landscaped parks. In many cases, the parks were developed directly from the water storage reservoirs that formed the water delivery and flood control systems for cities. For example, in 1870 the Los Angeles Canal and Reservoir Company built "Reservoir No. 4" in a dry chaparral ravine on the then sparsely populated western edge of the city. They filled it with diverted water from the Los Angeles River as part of a real estate sales scheme. The commercial venture ended in failure, but the city acquired the reservoir in 1892 and rechristened it as Echo Park (Masters 2014; Figure 2.9).

Figure 2.8: Los Angeles neighborhood, circa 1895. Note the zanja along the front of the properties. Several cut-outs or weirs are visible in this photograph, mimicking the structure of flood irrigation technology used in agricultural production at the time. These structural elements suggest the use of flood irrigation for domestic landscapes in the late 1800's in Los Angeles, California. Source: Historical Photo Collection of the Department of Water and Power, City of Los Angeles.

Despite the value that both residents and officials placed on irrigated landscapes, landscape irrigation was rarely explicitly recognized as a distinct aspect of municipal water use in the 19th and early 20th centuries. Moreover, the policy and legal frameworks that developed around water made a clear distinction between water for "domestic" purposes and irrigation water that was strictly for crop production. For example, the legal structure for water rights adopted by California in the 19th century mandated that irrigation was provided only for agricultural production, including small-scale production (kitchen gardens) within urban boundaries (Neuman 1998, Wilkinson 1990, Rodrigue 1996). This is despite the fact that the state's expanding population was increasingly blurring the distinction between urban and rural water users. Chief Engineer Hall referred to this period as the "Great Boom", when hundreds of acres of vineyards and orchards were divided into town lots and no longer irrigated (Hall 1886). At the same time, Hall's report lists one hundred twenty-five irrigators within the city of Los

Angeles, irrigating an average of twenty-four acres. The smallest, "*of whom there are many*" irrigating one-half acre or less (Hall 1888). When Los Angeles built the Los Angeles aqueduct they took care to note that the water was specifically slated for residential use and outside the conventions and restrictions that applied to irrigation water: "*The primary purpose of the Los Angeles Aqueduct is to bring Owens River water to Los Angeles for domestic use, and no perpetual right to water for irrigation should be given, either within or without the city*." (Board of Public Services Commissioners 1912). At the same time, the city developed plans to recoup the cost of running the growing water system by selling the "excess" water from the Los Angeles Aqueduct (water not needed for residential use) as irrigation water to adjacent districts. The 1912 annual report of the Water Board also notes public hearings where city residents offered to pay per acre surcharges to extend distribution lines for the purpose of delivering irrigation water.

A detailed discussion of water law and its history is outside the scope of this project, but current regulations refer to "beneficial use without waste" although the definition of the term varies by state. Some states specifically identify certain uses as beneficial in statutes or the state constitution, and expressions of beneficial use have shifted over time to reflect changes in values and scientific understanding (Neuman 1998). Urban landscape irrigation is not explicitly listed as a beneficial use in current laws, although the lists are generally interpreted as nonexclusive (Neuman 1998). Additional research is necessary to answer the question, but the recognition of ornamental landscaping as an important social element by Hall in 1888 might be the first reference to ornamental landscape irrigation as a legitimate use of water.

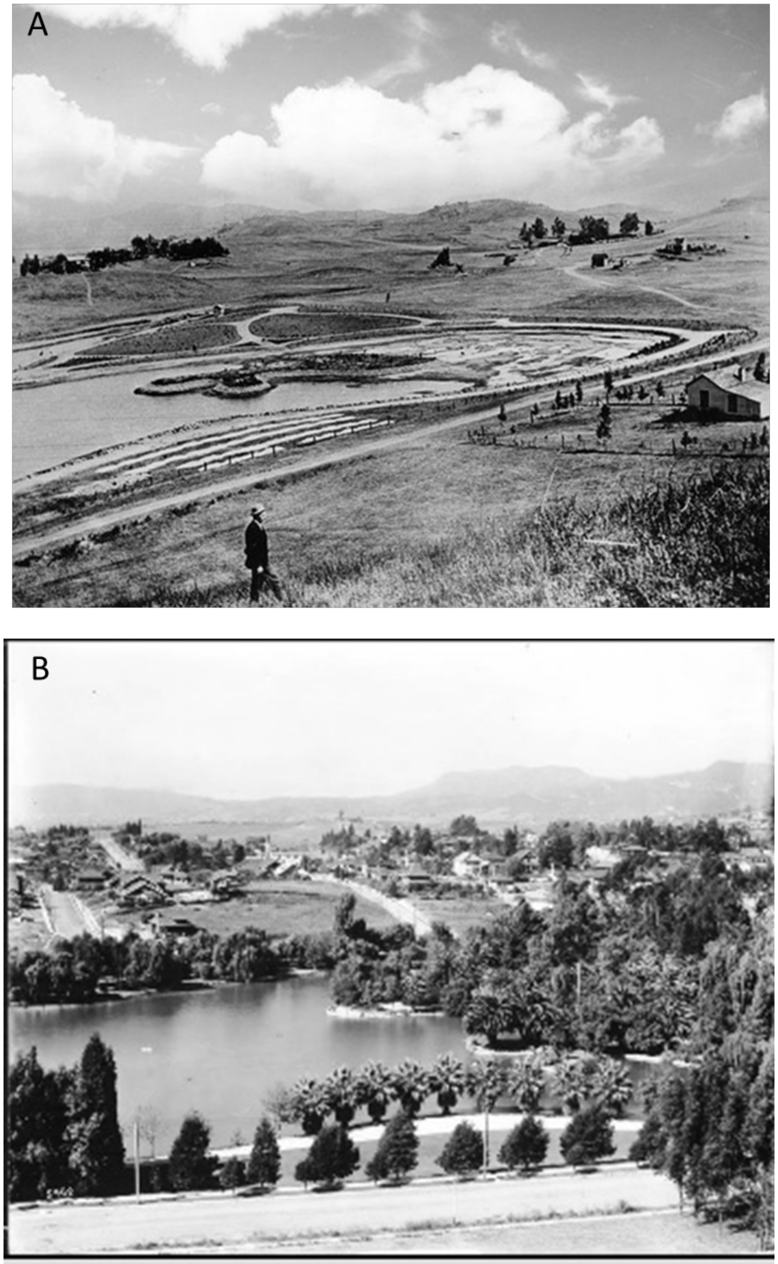

Figure 2.9: Echo Park was developed by the city of Los Angeles as a public park after acquiring a water storage reservoir created for a failed real estate venture. A) The park in 1894 soon after it opened. B) A view of the park in 1911 looking roughly in the same direction. The landscape design for the park was based on an English model and included lawns, a range of native and non-native perennials, and annuals. Sources. A) Los Angeles Public Library Photo Collection, https://calisphere.org/item/f7d3faa9923f624cc098a36729650782/ ; B) USC Libraries - California Historical Society Collection, http://digitallibrary.usc.edu/cdm/singleitem/collection/p15799coll65/id/4516/rec/3

Water storage, distribution, and pricing

In the 18th and 19th centuries, municipal water systems throughout the West were largely extensions of the distribution and allocation systems that had developed to deliver irrigation water. Throughout much of Spanish America, this was the communal acequia system. However, beginning in the 19th century private companies began to build water distribution networks, often associated with land development schemes. Private purveyors, such as the Los Angeles Water Company, began to charge fees for water use, although monitoring actual use was often difficult. In many cases, the companies utilized elements of the historic acequia to distribute water and collect fees. In the mid-1800's Los Angeles, water was withdrawn from the Los Angeles River and moved through zanjas to homes (Figure 2.10). A "Zanjeros" (ditch rider) was hired by the Los Angeles Water Company to control water flow through headgates at individual properties (Water and Power Associates n.d.). A patron's headgate was opened once the proper fee was paid. The fee was based on the quantity of water each property used, and was measured in "miner's inches," a unit of measure defined as the rate of water flow in a miner's sluice through an orifice one inch square, or one inch in diameter through a two-inch thick plank with a head of six inches. This was generally considered to be approximately 1.5 cubic feet per minute, or 11.25 gallons per minute (Hooten Jr. 2009). Photos of the period, and landscape designs included in Scott (1870) indicate that many residential plots were relatively large (the half-acre plots discussed by Hall (1888)) and the dominant irrigation use was for ornamental plantings. Average irrigation costs at the time were one dollar per acre for irrigation (Hall 1888), which suggests the average Los Angeles homeowner was paying a half dollar per year for irrigation water use in the late 19th century (equivalent to approximately $12.70 U.S. in 2018).

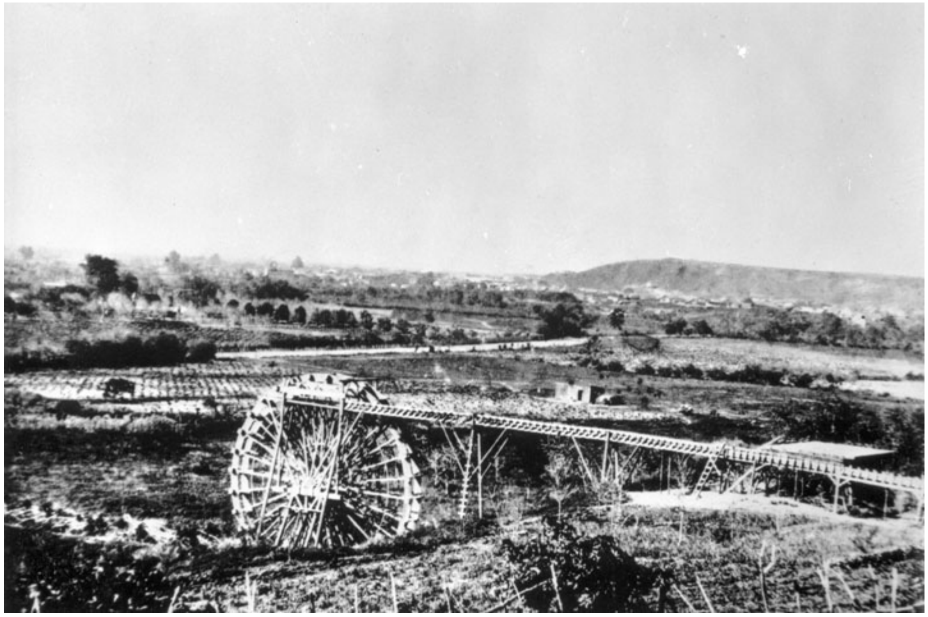

Figure 2.10: 1863 water wheel on the Los Angeles River at start of the Zanja Madre (mother ditch), LA's original aqueduct. Source: Los Angeles Public Library.

However, as urban populations boomed in the latter half of the 19th century, residential demand for water began to outpace the Zanjero's ability to provide and keep track of it. The amount of water used was often estimated, and fees collected by water companies rarely covered the costs of supplying water and monitoring its use: *"…while the average cost of water to the irrigator is somewhat less than 1$ per acre per annum, the cost to the public is $5.37 for every acre now irrigated inside the [Los Angeles] city limits*" (Hall, 1888). In addition, as cities became denser the system of open ditches became increasingly costly to maintain, created sanitation issues, and were hard to fit into the crowded city geography of small subdivided lots. By the 20th century many cities had embarked on ambitious moderation plans that included replacing the ditches with a network of buried cast iron pipe and installing individual water meters. In addition, many private companies were reorganized as public utilities. In 1902, the City of Los Angeles assumed ownership of the Los Angeles Water Company including the 302 water meters that were then in service. Ten years later in 1912 there were 49,140 meters in service across the city (Board of Public Services Commissioners, 1912). One important consequence of widely implementing metering was to foster conservation. In the first few years after the metering program was initiated, per capita water use in the city dropped by a third (Water and Power Associates, accessed 30 September 2018).

Water capture and storage was a concern for growing cities as indeed it was for the broader economic development of the west. Agricultural interests lobbied for the establishment of a system of catchment basins for all agricultural lands west of the 100th meridian – a longitude representing the line between the moist east and the arid west in the United States. The National Irrigation Congress had pressured the federal government since its founding in 1891 and was instrumental in securing federal support for a system of reservoirs.

> "*The problem of the development of the greater West is in large part a problem of irrigation. I earnestly believe in the national government giving generous aid to the movement, for it is not possible, and if it were possible, it would not be wise to have this storage work done merely through private ownership; and owing to the peculiar necessities of the case, much of the work must be done by the National and not by any State government*." (President Theodore Roosevelt. November 16, 1900; letter read before National Irrigation Congress, Chicago. The Forester, December 1900. Source: Theodore Roosevelt Association (2017).

In contrast, many cities developed their own water capture and storage systems that were largely independent of and parallel to the systems developed for agriculture. At the start of the 20th century many cities aggressively used their money and growing political influence to fund and build systems that were dedicated to residential use. In addition to building the Los Angeles Aqueduct, the City of Los Angeles procured water rights throughout much of southern

California, requiring new urban and suburban populations to become incorporated into the city in order to receive water for domestic or irrigation purposes (Rodrigue 1996). As communities developed, reservoirs began to be designed to include recreational opportunities for growing numbers of urban and suburban residents who were free of the responsibility of daily farm chores and had incomes and schedules that allowed free-time activities. This changing demographic spurred a significant shift away from the purely agrarian focus of water use that had dominated in the early and mid-19th century.

The development of urban irrigation technology

During much of the 19th century, innovations in irrigation design and technology were focused on agriculture. Concerns about water quantity and efforts to secure a consistent supply of water for agricultural production had been discussed since the early 1800's. As urban population grew and agricultural production expanded throughout California, the development of rules, laws, and regulations managing water allocation was viewed as necessary (Bell 1991, Neuman 1998, Wilkinson 1985). However, the condition of irrigation and water storage facilities was unknown after the California Gold Rush, and this lack of information stimulated creation of the first office of the State Engineer of California in 1878. William Hall, the first State Engineer, was tasked with assessing the current condition of irrigation in California and recommending future direction for the administration of the state's water resources (Hall 1886). Final reports submitted by Hall in 1888 raised questions concerning the efficiency of flood irrigation; the most common irrigation system at the end of the 19th century. The immediate response to Hall's report seems to be the manufacture and marketing of cement, iron, or masonry pipe as an improvement over the *zanjas* common in southern California (Figure 2.11). The timing of new systems for irrigation may have been a coincidence, but California was beginning to address water use efficiency in agricultural production and the markets were responding.

Many of the improvements in irrigation technology that were developed for agricultural systems were later adopted or modified for use in urban or suburban landscapes. Wood, clay or concrete pipe replaced many of the irrigation ditches in both agricultural and urban settings (Water and Power Associates n.d.) in an attempt to reduce water loss inherent with open canals in arid or semi-arid environments. In agricultural systems, piping was used initially for replacing main canals or ditches, and later adopted to provide water at regular spacing in fields and orchards.

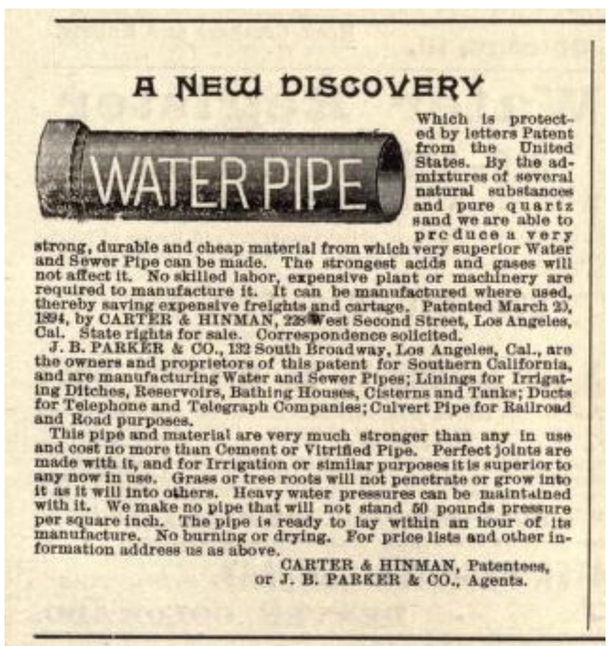

Figure 2.11: Advertisement for pipe; 1894. The uses listed include linings for irrigation ditches, reservoirs, bathing houses, cisterns and tanks. From: The Irrigation Age. Chicago 1894. Source: Smithsonian Institution; Biodiversity Heritage Library. https://www.biodiversitylibrary.org

Hand watering of agricultural fields was suggested by advertisers in *The Irrigation Age* magazine as a method of increasing irrigation efficiency. The development of hydrants and check valves ensured a constant supply of water with pressures provided by newly designed pumps consistent enough to push water through hoses connected to hydrants. Layout of the recommended pipe and hose irrigation system of the late 1870's is nearly identical to how conventional irrigation systems are currently designed for urban landscapes (Figure 2.12). Present-day industry standards recommend underground pipe with a number of risers and distribution heads in a design for head-to-head coverage in lawns and shrub beds (Irrigation Association 2014a). The pipe and hose arrangement described in Stewart (1877) appears to be the first irrigation system designed to provide water on a similar layout (Figures 2.13-2.14).

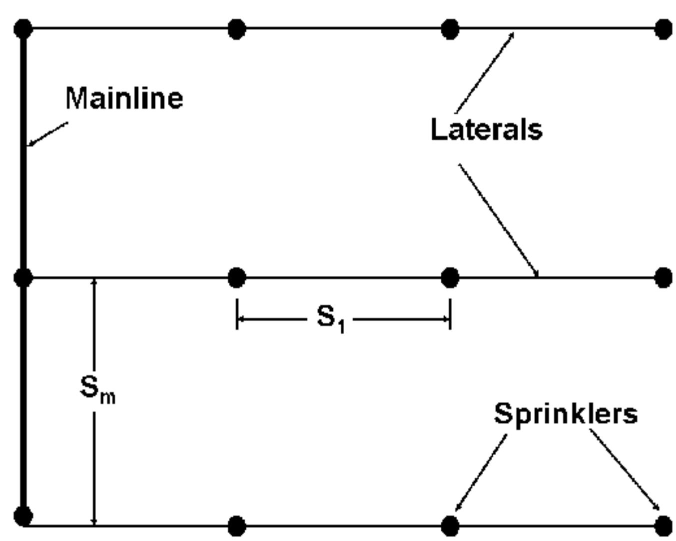

Figure 2.12: Present-day schematic of a standard irrigation system layout. Note the similarities between elements of this system and the 1877 layout described by Stewart (1877). Both systems use main line and laterals, with sprinklers instead of hydrants spaced evenly along the lateral pipes. From: (Fedler, Borrelli and Duan 2009).

Steward's design (Figure 2.13) describes a main pipe supplying water from a well to lateral pipe on which hydrants are placed at even spacing (200 ft.). The irrigation system is pressurized by a force pump; a technological improvement to gravity fed systems that gained popularity in the mid 1800's. Steward states this method, utilizing attached sprinklers, had been used in England for several years. In these types of systems, underground pipes were often fitted with threaded couplers or check valves (i.e. the KT Valve) which allowed hydrants, sprinklers, or hoses to be easily attached. Designs of modern systems include the same elements, but hydrants have been replaced by irrigation heads, and force pumps replaced by pressurized municipal water supplies in urban areas.

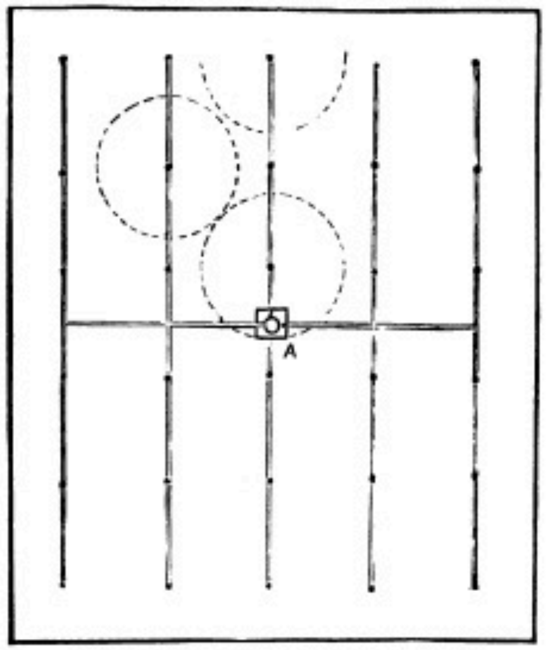

Fig. 22.—PLAN OF PIPES AND HYDRANTS.

Figure 2.13:"[A] well, with reservoir, windmill and force-pump, is situated in the center of the plot to be irrigated at A." "The points marked upon the lateral pipes shove the positions of the hydrants, and the dotted circles around a few of them show the extent hose covers the ground." From: (Stewart 1877)

The end of the 19th century also saw the development of irrigation technology that was specifically designed for residential landscaping. An 1872 patent for an *Improved Portable Garden Sprinkler* (Patent number 129,125) by John Gibson of San Francisco, California appears to be the earliest garden sprinkler patented in the United States (US Patent and Trademark Office nd). What this sprinkler improved upon is not indicated or implied in the patent description, but the title suggests earlier sprinkler technology. The patent description states this sprinkler can be mounted on a portable frame or stand and connected with the main water pipe (Figure 2.15). The drawing indicates a threaded pipe, possibly fastening to a hydrant mount or riser as described in Steward's 1877 treatise on irrigation for the farm and garden, although J. Gibson's patent precedes Steward's work by five years. This discrepancy implies pipe and sprinkler technology was in use prior to 1872, possibly based on the English system mentioned in Steward (1877).


Fig. 21.—IRRIGATING BY PIPES AND HOSE.

Figure 2.14: The new system of using pipes and hydrants depended on gravity feed from a tank or reservoir, and was reported to provide irrigation for nearly one acre per hydrant. Hydrants were spaced at approximately 200 feet apart. India Rubber Hoses, and a flattened nozzle were recommended as new technology used in irrigating agricultural properties. Although a man was expected to be able to irrigate 5 acres per day, this system was probably used in smaller scale agricultural production or small urban or suburban gardens. Source: (Stewart 1877)

An interesting contrast to common practices of the late 19th century is Scott's 1870 treatise on suburban home grounds. His popular *Suburban Homes* includes a discussion on irrigation as related to plant establishment and vigor. But the discussion focuses on allowing the soils to dry to stimulate air movement through the soil: "*Imperceptibly, but surely, the earth* *beneath our feet is being warmed and fertilized by the action of the air upon it, whenever we invite the air in, by drawing the water out*" (Scott 1870). This statement raises questions about flood irrigation causing soil health and fertility problems in urban properties in the late 19th century.

New tools were developed for the emerging urban and suburban gardener and quickly brought to market, including hand pumps, lift pumps, nozzles, spray heads, and sprinklers. Irrigation was recognized as a significant influence on the economy of the American west in the late 19th century (1890). This period also saw the fledgling development of an industry that specifically served the needs of residential landscapes. The market for this industry was partly the growing number of gardening and horticultural enthusiasts. However, in addition, well maintained and aesthetically pleasing home landscapes were also becoming social norms. Suburban residents formed a social network where the appearance of affluence was an important value (Trachtenberg 2007); a fundamental shift from earlier agricultural life. While maintaining a level of aesthetic quality was important, pursuits other than working on garden maintenance often took precedence (Mead 2004). A rapidly evolving irrigation industry promised relief from the necessity of caring for home gardens and landscapes, supplying goods and services to efficiently maintain suburban America. Markets were expanding concurrent with this change in community and social structure, summarized in F.H. Griswold's article on the conversion of farm land to suburban development at the turn of the century (Griswold 1911).

Descriptions of landscape design and maintenance methods during this period still used the language of agricultural systems, including terms such as *lawn shearing* or *meadow treatments* (Anderson 1903, Scott 1870) that suggest a strong cultural view of urban landscapes as an extension of agricultural practices. Irrigation design for an expanding suburban population also reflected agricultural practices; first utilizing flood irrigation, then as technology was developed, through underground pipes and associated methods of water distribution previously used only for crop production.

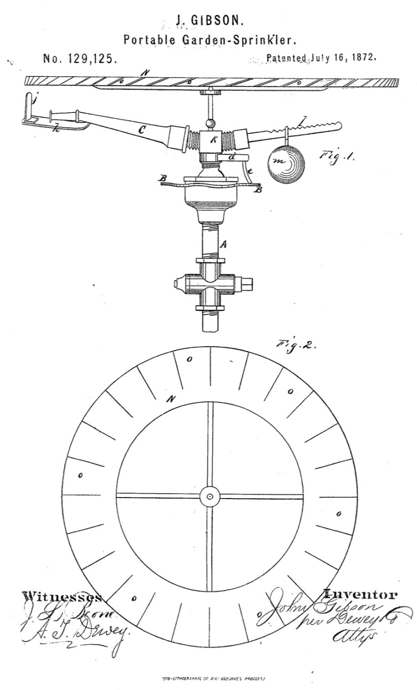

Figure 2.15: John Gibson's Improved Portable Garden Sprinkler. This is the earliest known patent for a garden sprinkler in US Patent and Trademark Office records. July 16, 1872. Patent no. 0129125. Source: United States Patent and Trademark Office. http://pdfpiw.uspto.gov

Twentieth Century development of a landscape irrigation industry

As stated by the National Irrigation Congress in 1894, the future of the west was tied to the future of irrigation, and the continued development of California was dependent on providing a consistent supply of water; *"… as fast as the [irrigation] system is put into good order and condition and the canals are given their proper supply of water with reliable certainty, the lands will be entered upon and improved…"* (Schuyler 1906). Concerns over the availability of water increased in the early 20th century stimulating the development of conservation measures designed to increase supply and sustain population growth. *"There is an obvious limit to the supply [of water], therefore, in spite of all that can be done in conserving the supply"* (LA Times 1904).

A complete history of the infrastructure necessary to maintain a steady supply of water to irrigators in California has been documented in other studies (Hundley Jr. 2001, Kahrl 1982, Rodrigue 1996, Theodore 2014, Vorster 1992) and is outside the scope of this work. But the growth of the urban irrigation industry was highly dependent on the work of City, State, and Federal governments in procuring water rights and supplies sufficient to support rapid population growth in the western United States.

Market Development

As urban and suburban communities continued to expand in the early 1900's, the number of companies marketing irrigation supplies grew. Delivery methods were developed which aimed to reduce labor and provide increased efficiency in landscape irrigation, often marketed to small scale agricultural producers or home gardeners and adopted for use in urban landscapes.

A consolidated effort addressing the rapid expansion of the irrigation industry was soon deemed necessary by industry leaders, stimulating the establishment of the Association of Sprinkler Irrigation Equipment Manufacturers (ASIEM) in 1949 for the purposes of "*combining the mutual interests of all who are concerned with developing and increasing the use of sprinkler irrigation systems*." (Irrigation Association 2018). The Association focused on agricultural irrigation and ensuring a supply of aluminum for the manufacture of irrigation pipe through the Korean War (1950 – 1953). Through continued lobbying in Washington D.C., the sprinkler irrigation industry emerged as an established member of the business community. Overhead sprinkler irrigation was heralded as the greatest U.S. agricultural achievement since the mold-board plow (Irrigation Association 2018).

In 1953, the ASIEM was formally incorporated as the Sprinkler Irrigation Association (SIA) with the stated objective of working toward the acceptance of sprinkler irrigation in agricultural production. Over the next 25 years, the SIA rapidly grew to prominence as an irrigation trade association by fulfilling a number of goals, including creating a popular educational film "Weather or Not" jointly sponsored by the National Fertilizer Association and displaying the benefits of irrigation and chemical fertilization (Irrigation Association 2018). In 1976, the focus of the SIA moved beyond sprinkler irrigation and changed its name to the Irrigation Association (IA).

The efforts of organizations like the ASIEM and popular publications or magazines such as *House and Garden* (first published in 1901) or *Better Homes and Gardens* (first published in 1922 as *Fruit, Garden & Home*) encouraged gardening and landscaping to beautify an urban property, and as the United States entered two World Wars, as a way of providing food during periods of rationing. Irrigation was essential in semi-arid environments common in the western U.S., requiring innovation to meet a growing demand for irrigation at scales commensurate with urban gardens.

Industry Competition

The post-World War II irrigation industry expanded rapidly. Goodyear Rubber Company and other manufacturing leaders briefly dabbled in the irrigation industry but eventually focused on other products, leaving five major companies providing most products for urban irrigation. Of 1000 patent applications from 1953 to 2015, Hunter Industries was granted 4.4% of the patents, The Toro Company received 3.6%, Rain Jet 2.7%, Kah Jr. Carl L.C. 2.1%, and Rain Bird 1.8%.

The pattern of patents awarded per decade by company reflects competition between these major suppliers.

From 1953 to 1974, Rain Jet Corporation, a California company established in 1954, nearly dominated the irrigation industry. The company is no longer operational, and corporate records indicating a dissolution date are unavailable. The Toro Company, established in Minneapolis, Minnesota in 1914, and Kah Jr. Carl L.C., the parent company of K-Rain Manufacturing Corporation headquartered in Florida (originally filed as a corporation in 1971) provided most irrigation patent applications from 1974 to 1992, when the three remaining viable companies shared market dominance with one recently formed competitor; Hunter Industries, founded in 1983 and centered in San Marcos, California.

Mid-20th Century Technology

The industry changed significantly during WWII. Aluminum pipe was developed as part of the war effort and soon replaced iron or wooden pipe in agricultural irrigation systems. Technological advances in mechanization, enhanced by the rapid development of inexpensive chemical fertilizers and pesticides since 1945 increased farm productivity and stimulated innovation in the associated irrigation industry (Dimitri et al. n.d.). An increased need for irrigation parts and supplies inspired manufacturing and helped establish irrigation companies as an important element in local economies.

Rapid growth in the number patents filed occurred between 1960 and 1999 (Table 2.1), increasing by 73% over the previous 40-year period (1920 – 1959). Several contributing factors are plausible: 1) irrigation technology development is tightly correlated with the rise in agricultural production following WWII; 2) rapid urban and suburban population growth created a burgeoning market for residential irrigation goods and services; 3) economic prosperity and industry marketing increased perceived need for residential irrigation goods and services; or 4) continued concerns over water supply and distribution efficiency increased demand for improvements in irrigation technology. More likely, the rapid rise in irrigation innovation and patent applications was a result of a combination of these factors. Social, economic, and environmental considerations seem to have played a part in the rapid expansion of the irrigation industry in the mid-to-late 20th century.

Table 2.1: The number of patents filed with the U.S. Patent and Trademarks Office, 1872 to 2015 as reported by(Google Patents, (2018). However, a search of the US Patent and Trademark office database generate results ranging from approximately 1300 to 34,000 patents for irrigation technology filed between 1872 and 2015. The wide range of results was dependent on parameters entered in the search engine. This table indicates relative growth of the irrigation industry for that period and does not provide an accurate count of patents granted. The exponential growth in the 20-year period from 1960 to 1980 may be a response to establishment of the Sprinkler Irrigation Association and marketing efforts of popular gardening magazines.

Time period	Number of lawn and landscape irrigation patents granted
1872-1899	8
1900-1919	13
1920-1939	40
1940-1959	44
1960-1979	149
1980-1999	165
2000-2015	180

Heermann (n.d.) suggests the increased availability of plastics and the development of computer controllers for irrigation scheduling in the 1970's led to significant increases in the use of sprinkler irrigation in agricultural systems, but notes that most developments in irrigation over the last century have focused on water delivery subsystems and neglected innovation to improve efficiency of water use (Heermann n.d.). That sentiment is supported by Pair (1970) in his discussion on the use of mechanized sprinkler systems in agricultural production, a technology promoted to increase the efficiency of water delivery. He states that in 1970, merely 20% of all agricultural production in the United States is irrigated by sprinklers, but predicts that rate will rise to greater than 80% as water supply becomes more critical (Pair 1970).

Competing demands for water

The administration of water in the western U.S. still focuses on the same topics of supply and demand discussed in the mid and late 19th century. Balancing the need for urban water with agricultural production in the western U.S. often denied or delayed developing solutions to long-term supply issues. For example, in 1914 California's water rights administration system was responsible for allocating water supplies for beneficial uses in an "orderly manner" (Theodore 2014). However, since its establishment, the water board has issued water rights over five times the state's annual supply (Little Hoover Commission 2010). Current work in water supply management in California focuses on balancing agricultural use with expected increases in urban water demand and changing social values on environmental quality and concerns about climate change (Brachmann 2015, Little Hoover Commission 2010). Identical issues are discussed in the Upper Deschutes Basin Study in Oregon. Over-allocation of water resources is described in the 2017 draft report, and alternative approaches to water conservation address balancing agricultural use with urban demand and social concerns over environmental conditions and endangered species (Bureau of Reclamation 2017). Alternatives include increasing or changing the location of storage facilities (reservoirs) and providing economic incentives for irrigators to utilize existing and future technology designed to increase application efficiency. Studies addressing water supply, allocation, and efficiency have also been initiated by the Bureau of Reclamation in the Rio Grande Basin in New Mexico and the Eloy and Maricopa-Stanfield

Basins in Arizona (Bureau of Reclamation, 2017). Herrmann (n.d.) discusses a 2003 drought in Colorado as a major problem for irrigators and states "*the matter is in the hands of the Water Courts…*", the outcome seemed uncertain. Urban landscape water use, although often reported as a minor contributor to overall water use (Bureau of Reclamation, 2017), is frequently addressed in municipal resource management or litigation as an easy target for conservation.

The increasing frequency of studies addressing water allocation and use throughout the western United States supports Pair's 1970 prediction about the critical nature of water supplies. End users of irrigation technology are becoming increasingly knowledgeable about the need for water conservation and efficiency in application, and are demanding innovations to meet those needs (Dimitri et al. n.d., Brachmann 2015). Irrigation supply companies, such as Hunter, Toro, and Rainbird, are responding to social pressure by stimulating a nearly constant flow of new products and methods designed to maximize the efficiency of water use.

The future of urban landscape irrigation will undoubtedly follow the same path as it has over the past 150 years, adopting innovations and methods from agricultural irrigation. But early designs to increase irrigation efficiency focused on making human effort more effective and were developed to reduce excess labor common in agricultural production. Recent innovation attempts to increase the efficiency of developed technology such as timers, sprinkler heads, and distribution systems. This subtle shift in approach reflects broad social values associated with the "Great Acceleration", an age where innovation and development of new technology outpaces the ability of people to adapt (Friedman 2016). This social phenomenon may partially explain the general delay in adapting new water use reduction methodologies in the irrigation and landscaping industries.

Summary

A review of historical literature, photos, patents, and reports reveals a consistent theme affecting the evolution of urban irrigation: concerns over water supply. The availability of water has been a consistent issue in the semi-arid western United States since people first constructed permanent villages. The capture, distribution, and application of water in the west was critical to the survival of a community and required innovation and effort to meet that need. As populations grew and knowledge was transferred, efforts increased to include sometimes herculean efforts (such as the Whitney Siphon), and innovation in developing technology to improve efficiency in water use. This has been shown as a consistent topic since the 1700's in California and is reflected in the recorded history of the state.

Ornamental landscape irrigation developed as a direct lineage from agricultural production. Methods and technology developed for growing crops in the arid west was adopted for urban landscape irrigation in California during the mid-19^{th} century and the technology spread from southern California throughout the west. Flood irrigation, the common irrigation technique for agrarian populations in the early 19^{th} century, was adapted for use in the newly urban and suburban developments of southern California. Advancements in agricultural techniques were quickly adapted to landscape irrigation from the mid-1800's through the early 20^{th} century, but an exponential change in the rate of innovation and technological advancement is reflected in the number of patents and the growing number of companies offering "new" products for both agricultural systems and home landscapes beginning in the 1960's and continues today.

Similar themes are central to current studies in water use and allocation throughout the western United States. Social values have shifted to include concerns over environmental quality – a subject that didn't appear prominently in historic literature – but anxieties over water supply and allocation still dominate efforts to manage water use.

However, growth and expansion in the irrigation industry now focuses on improving the efficiency of existing technology, contrasting with earlier efforts to develop new methods and technologies. Perhaps drought conditions in much of the United States and around the world may be the catalyst needed to stimulate future innovation in irrigation efficiency, much as two World Wars stimulated innovation in agricultural production.

Chapter 3 - Water Stress Patterns of Xerophytic Plants in an Urban Landscape

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Abstract. The efficient use of water in urban landscapes is a common objective throughout the western U.S.A. Vegetative species promoted for their drought tolerance characteristics are often included in landscapes designed for resource conservation. However, water requirements of most common landscape species have not been quantified. This is especially true for xerophytic species. This lack of data is a significant constraint on the design of efficient irrigation systems and management practices affecting urban landscape water use. Current irrigation practices fail to consider the unique physiology of xerophytic species, and irrigation scheduling models may not be appropriate for xeric landscapes utilizing xerophytic vegetation as a primary method of reducing water use.

This study describes the seasonal pattern of growth and xylem water status for four regionally native xeric shrub species installed in an unirrigated urban landscape in the semi-arid environment of central Oregon, U.S.A. The four species (*Artemisia tridentata*, *Holodiscus microphyllus* (previously *H. dumosus*), *Ericameria nauseosa*, and *Ribes cereum*) exhibited substantial growth over 18 months without irrigation and in a heavily modified urban soil profile.

Water potential in the four species was correlated with soil moisture level but not with reference evapotranspiration or vapor water deficit. In *A. tridentata* and *H. microphyllus,* xylem water potential became more negative over the growing season, tracking the seasonal decline in soil moisture. In contrast, *E. nauseosa* and *R. cereum* tracked soil moisture early in the season but became unrelated to soil moisture in the driest months, suggesting different drought adaptation strategies in these species. Three of the four species showed no signs of visual drought stress and maintained acceptable aesthetics even as soil moisture dropped below10%. However, *R. cereum* exhibited a drought dormancy strategy which made it less aesthetically desirable by homeowners. These results suggest that extreme xerophytic shrubs provide an opportunity for significant water use reduction in urban landscapes.

Key Words: Urban Landscapes, Xeric, Native Plants, Irrigation Budgeting, Water Potential

Introduction.

Many urban centers in the western United States are in ecoregions (Omernik 2004) that experience generally low or markedly seasonal patterns of precipitation that create prolonged periods of soil water deficit during the year. As a result, most urban landscapes in the region use seasonal irrigation to maintain plant health and aesthetic quality. However, urban water use has become a contentious subject. Water regulation in response to water scarcity often targets outdoor water use in urban landscapes as a significant tool for reducing overall municipal water use (Glenn et al. 2015, Hilaire et al. 2008, Hayden 2015, Qaiser et al. 2011, English, Solomon and Hoffman 2002). Such regulation is well targeted, as potable water used in urban landscapes exceeds the amount used in all agricultural production in the United States (Ferguson 1987, Smith and Smith 2013). In the western United States 50-60% of residential water is used for outdoor purposes, predominantly for urban landscapes (Bend 2011, Hilaire et al. 2008, Mini, Hogue and Pincetl 2014).

Consequently, local and regional governments are increasingly encouraging and even demanding more water efficient landscape designs. More broadly, there is a growing interest in developing more sustainable urban development. For example, the Living Building Challenge is a performance-based green building certification program managed by the Living Futures Institute (McLennan 2008). A primary design goal of the Living Building Challenge is resource conservation. Landscapes must balance the availability of on-site treated water with a calculated water budget reflecting the water use requirements of the constructed landscape. Water conservation is inherent in Living Building designs, and structures built under the Living Building Challenge must supply their own resources, including power and water. Each site is unique in its ability to provide those elements.

One approach to reducing the water footprint of urban landscapes is to broaden the use of species that have unique adaptations for tolerating extended periods of water stress. These species could be used to design landscapes that provide a range of functions such as aesthetics, but that also have very low or even no irrigation requirements. For example, many perennial shrubs native to the western United States deserts have extreme drought adaptations that allow them to thrive even in habitats that experience extreme water deficit (Smith, Monson and Anderson 1997).

However, a roadblock to designing extremely low water input landscapes is that we have a generally limited understanding of how xeric adapted species respond to declining water availability. In addition, the few data that do exist generally come from field studies of plants in minimally disturbed natural habitats (Ehleringer et al. 1991, Mata-González et al. 2014, Volo et al. 2014, Webb et al. 1978). Urban contexts likely pose a unique set of environmental challenges that could interfere with the drought adaptations of xerophyte species. For example, urban soils are often compacted or have more restrictive soil volumes relative to rural or wildland soils (Craul 1991). Compacted soils can negatively affect root growth and reduce the water holding capacity (Benbough et al. 2005, Eavis 1972, Sims and Singh 1978). Almost no data exist that describe the ecophysiological response of xerophytic species in actual urban landscapes. This lack of information makes it difficult to develop appropriate plant palettes as well as appropriate recommendations for their management.

In this study, we evaluate the drought response of xerophytic plant species in an established urban landscape designed to emulate the ecological functions of a sagebrush-steppe plant association in the East Cascades Slopes and Foothills ecoregion. The landscape was designed to meet the water conservation standards under the Living Building Challenge, and was actively used by the landowners during the course of the study. We measured the water status and growth patterns of four native shrub species. We tested the association between xylem water potential, monthly evapotranspiration (ET), soil moisture level, and vapor pressure deficit (VPD). We also subjectively evaluated the aesthetic quality of the species through interviews with the property owners.

Materials and Methods

Study Site. We conducted the study at Desert Rain, a residence and demonstration site located in the urban core of Bend, Oregon (44^{o} 3' 10.87" N, 121^{o} 19' 17.67" W). Bend is a city of ~80,000 located in the East Cascades ecoregion (Omernik 2014) at 1,115 m elevation. The climate is semi-arid (Figure 3.1). Summers are typically warm and dry with an average daytime temperature of 25°C (June – September). Winters are normally cold, with annual precipitation falling as rain or snow. Average winter daytime temperature is 6°C (November – February). Average annual precipitation is 289 mm.

Dominant soils at the study site are *Wanoga* (35%) and *Fremkle* (30%) series *Vitrixerands* of the order *Andisols*, described as moderately deep, well drained sandy loam on volcanic uplands (NRCS 2014) containing an average 60% ash in the upper 35-60 cm and a high humus content in the surface horizon (Krasilnikov 2009). Mean annual soil temperature is 7.2°C. Remaining soils are classified as Rock Outcrop (NRCS 2014). Slope varies from 0% to 20% in the study area, with north/northwest aspect predominant.

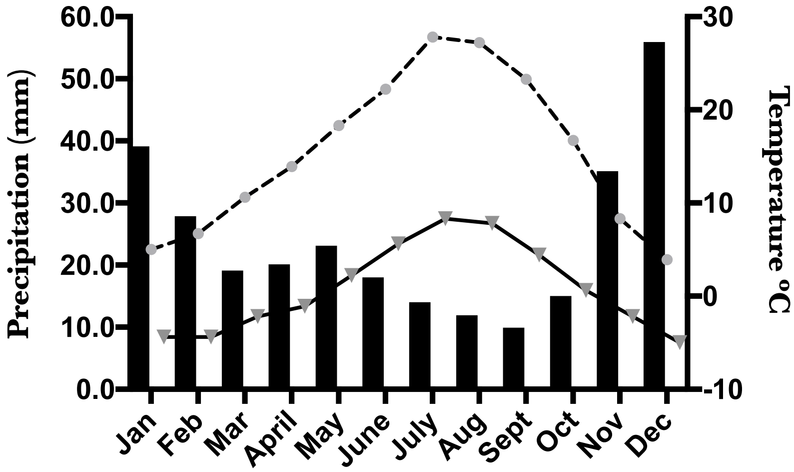

Figure 3.1: Climograph for Bend, Oregon U.S.A. Mean monthly precipitation (bars), mean daily high temperature (dotted line) and mean daily low temperature (solid line) are historical averages (1954 - 2015).

The study landscape covers approximately 168 m^2; roughly 5% of the entire property. The design intent was to emulate the structural and vegetative components of the sagebrush steppe plant association that is characteristic of the site, while enhancing the aesthetic considerations typical of a managed urban landscape. Construction included creation of rock outcrops, drainage patterns, and spatial distribution of plants to create resource islands; a critical structural and functional component of sagebrush steppe communities (Halvorson et al. 1994). The study portion of the landscape is unirrigated. No irrigation system was installed, nor has the study site received supplemental irrigation.

Thirty-eight native plant species were installed in the landscape in February and March 2015. Plants installed include 12 shrub species, 22 forbs, and four species of grasses. All shrubs and forbs were installed as one-gallon nursery stock, grasses were installed as a mix of 3.5 inch container and one-gallon nursery stock. All plants were propagated locally from propagules collected within the same East Cascades ecoregion as the study site (Omernik 2014).

Study plants. Four shrub species native to the East Cascades ecoregion were used for water use efficiency studies: *Artemisia tridentata* Nutt ssp. *wyomingensis* Beetle & Young (ARTRW8), *Holodiscus microphyllus (prev. dumosus)* var. *glabrescens* (HODU), *Ericameria nauseosa* (Pall. Ex Pursh), G.L. Nesom & Baird (ERNA10), and *Ribes cereum* Douglas var. *cereum* (RICE) (NRCS 2006).

Physical measurements. In August 2015, we installed a HoboWare model U30 weather station datalogger (Onset Computer Corporation, Bourne, MA) at the study site. We used the station to record volumetric soil water at 10 cm, 30 cm, and 60 cm depths, precipitation, and ambient air temperature. Readings were collected every five minutes and averaged every two hours, resulting in twelve records every 24 hours.

To assess physical changes in soil structure resulting from construction activities, we measured soil bulk density and porosity from samples collected at the study site and from a relatively undisturbed reference site within the same East Cascades ecoregion and soil series (44° 0'53.29"N; 121°17'14.80"W). The same ecological site type is reported for both the study and reference site. The dominant plant association for both sites is *Juniperus occidentalis* Hook/*Pinus ponderosa* Lawson & C. Lawson/*Festuca idahoensis* Elmer spp. *idahoensis (Natural Resources Conservation Service , NRCS 2014)*.

Soil samples were collected across a depth profile using an AMS Bulk Density Soil Sampling Kit (AMS, Inc. American Falls, Idaho). Samples were taken an 10 cm, 30 cm, and 60cm depths at the reference site and 10cm and 30cm depths at the study site. Samples from 60 cm depth were unattainable at the study site due to shallow bedrock. Ten 90.59 cm^3 samples were collected for each depth at the study site and the reference site. We estimated gravimetric soil moisture content by weighing samples at field capacity, then drying each sample in a microwave for three cycles of 5 minutes and weighing the dried samples. We estimated soil bulk density by dividing dry soil weight by volume and soil porosity according to (Thien and Graveel 2002).

Reference evapotranspiration. We obtained average monthly reference evapotranspiration (ET_{ref}) from the AgriMet Cooperative Agricultural Weather Network (Palmer 2008) calculated for the Bend, OR station (44.0475 N 121.32027 W; elevation: 1103 m), located 0.62 km south of the study property. Calculations utilize the Penman-Monteith equation.

We estimated daytime vapor pressure deficit (VPD_d) following (Murray 1967), with saturated vapor pressure estimates calculated following Jensen, et al. (1990).

Plant performance. At the study site we identified four target individuals of each species that were located within 5 m of the installed weather station. We measured monthly midday xylem water potential (Ψ) for each target individual using a model 1505D pressure chamber (PMS Instrument Company, Albany, Oregon). Five replicated measurements were made of each individual during each sample period. Measurements throughout the study period were made from the same individual plants.

We estimated the change in above-ground biomass of the target individuals over the 18 months since they were planted in the landscape. We destructively sampled representative 1.0 gallon nursery stock from the same nursery stock as the planted individuals. All above-ground biomass was removed, dried at 116°C for 48 hours, and weighed. Because removing entire plants from the created landscape was not approved by the property owner, we estimated above ground biomass of the established target plants using the reference unit technique (Bonham 2013). We destructively harvested a representative 10% sample of the canopy of each target individual. The representative samples were dried, weighed, and used to estimate the above ground biomass of whole plants by extrapolation as in (Evans et al. 2013).

We assessed the rooting depth of each target individual by excavating root systems of individual plants to a depth of 60 cm, where possible. Excavation of deeper soil layers was inhibited by shallow parent material characteristic of the study site. We traced tap and fibrous roots back to the crown of the plant to ensure measurements were for the correct species. Roots extending beyond 60 cm depths were noted.

Aesthetic quality. Plant health and aesthetic quality was qualitatively assessed by the lead author and the homeowners. Owners were informally interviewed twice a month about perceived landscape health and visual quality.

Statistical Analysis. We described the associations between monthly xylem pressure and volumetric soil water content at each measured depth using Pearson correlation. We tested whether soil properties across the depth profile at the study and reference sites differed from each other using two-way analysis of variance. Statistical test were conducted using GraphPad Prism version 7.0 GraphPad Software, La Jolla California USA.

Results

Patterns of plant water stress. The xylem water potential of *A. tridentata* and *H. microphyllus* progressively increased (became more negative) over the summer and fall. In contrast, the water potential of *R. cereum* and *E. nauseosa* initially increased into early summer but then decreased in late summer and early fall. *Ribes cereum* and *E. nauseosa* also had generally less negative xylem water potential over the season than *A. tridentata* and *H. microphyllus* (Figure 3.2). Xylem water potential of the four species was strongly correlated with soil moisture content at all three depths (Table 3.1). However, the water potential of both *A.*

tridentata and *H. microphyllus* more closely tracked the seasonal decline in soil moisture than did *R. cereum* or *E. nauseosa* (Figure 3.2).

Xylem water potential was only weakly correlated with ET_{ref} and VPD_d in all four species (Table 3.1). Both ET_{ref} and VPD_d reached their maximum observed levels in early summer, then declined over the next four months (Figures 3.3, 3.4).

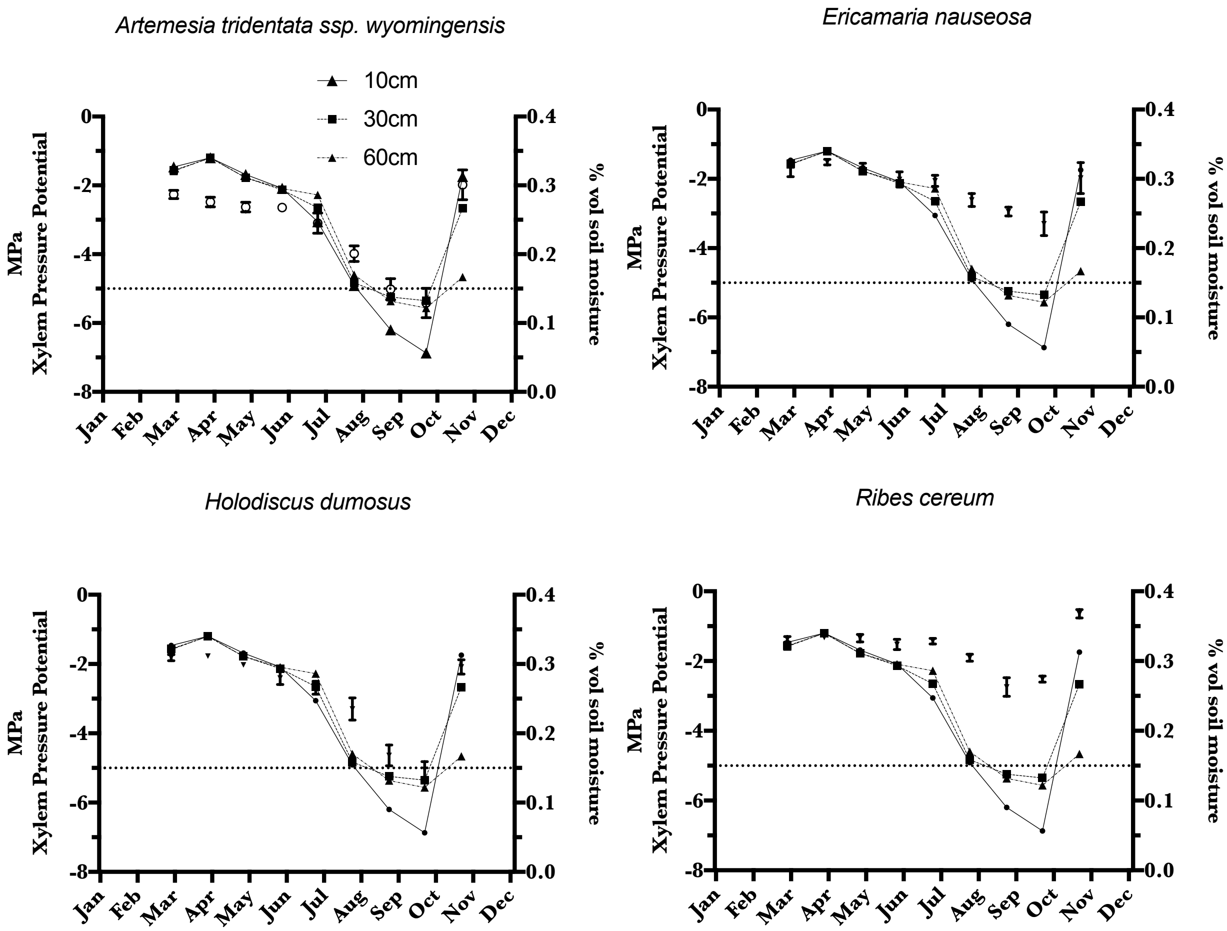

Figure 3.2: Monthly xylem water potential (dots) over the course of a year for four xerophyte plant species in an urban residential landscape in Bend, Oregon, U.S.A. Volumetric soil moisture at 10cm, 30cm, 60cm is plotted as solid lines. The dotted line at 15% volumetric soil moisture is a generally accepted permanent wilting point.

Plant growth and health. Significant biomass production was recorded for all four study species within the first 18 months of growth. Each shrub was installed as one gallon nursery stock with above-ground biomass ranging from 5.1 to 14.1 grams, and exhibited production rates from 400 to 1200 percent (Table 3.2). Rooting depth for each individual plant exceeded 60 cm in 18 months, suggesting each plant quickly accessed available soil moisture at depths exceeding the capability of most irrigation systems.

Table 3.1. Degree of correlation between measured xylem water potential, reference evapotranspiration (ET_{ref}) and mean daily vapor pressure deficit (VPD_d) for four xerophyte plant species in an urban residential landscape in Bend, Oregon, U.S.A. Values are Pearson correlation coefficients. ARTRW8 = Artemisia tridentata ssp. wyomingensis; ERNA10 = Ericameria nauseosa; RICE = Ribes cereum; HODU = Holodiscus dumosus;

Pearson correlations water potential	% Soil Moisture			ET_{ref}	VPD_d
	10cm	30cm	60cm		
ARTRW8	0.98	0.92	0.74	-0.55	-0.14
ERNA10	0.98	0.97	0.88	-0.52	-0.22
RICE	0.90	0.80	0.56	-0.52	-0.09
HODU	0.99	0.94	0.82	-0.52	-0.18

Aesthetic quality. Three of the study species, *Artemisia tridentata*, *H. microphyllus* and *E. nauseosa* did not exhibit visual indicators of drought stress and retained their aesthetic value throughout the growing season, even as volumetric soil moisture declined below 10%. In contrast, *Ribes cereum* dropped much of its leaves in late summer and displayed signs characteristic of a summer deciduous strategy for surviving drought. Generally, the homeowners were very pleased with the visual quality and apparent health of the landscape, and the rapid growth of the plants. They did express concern about the visual stress of the *Ribes* in August and continued their concern through September.

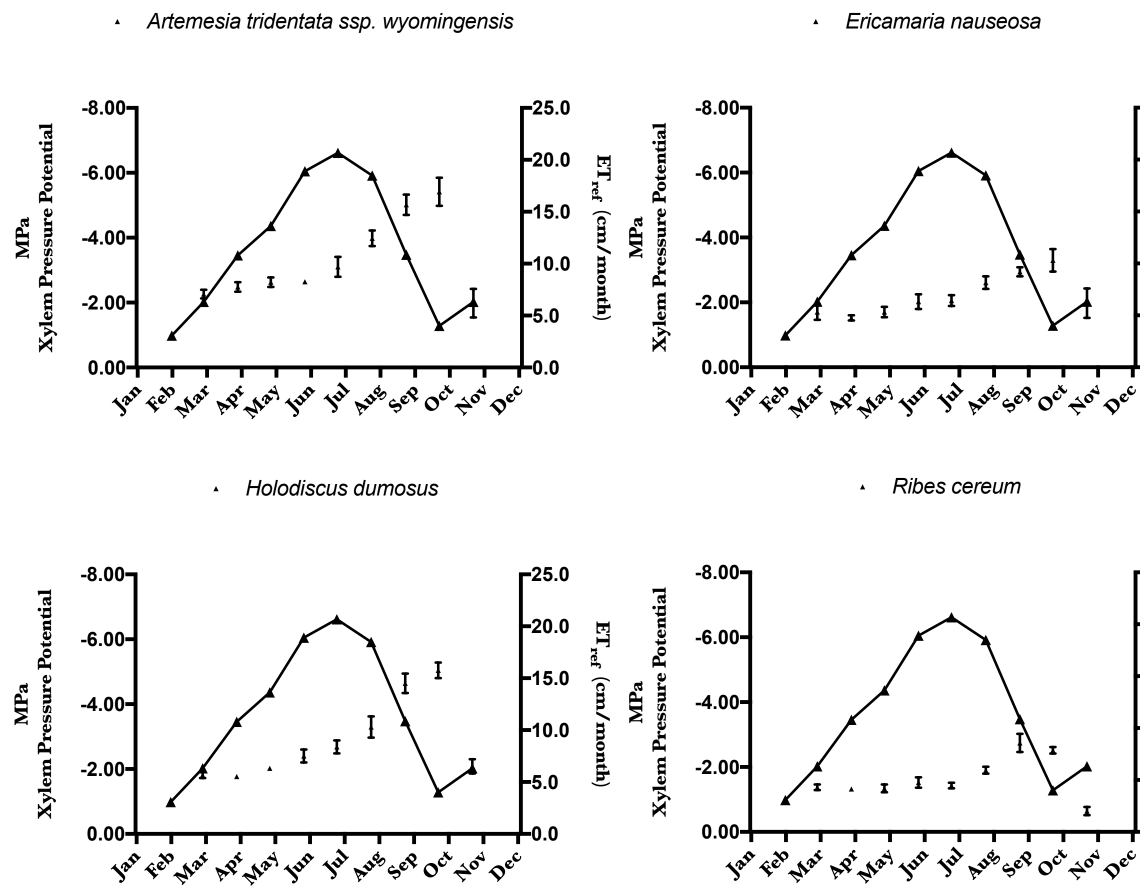

Figure 3.3: Monthly xylem water potential (dots) over the course of a year for four xerophyte plant species in an urban residential landscape in Bend, Oregon, U.S.A. Reference evapotranspiration (ETref) is plotted as a solid line.

Soil characteristics. Soil characteristics at the study site were generally similar to those at a nearby reference site (Table 3.3). There were no significant site or site x depth interaction effects for any of the measured soil variables (Two way ANOVA, $p > 0.1$, d.f. = 1,16).

Discussion

The species examined in this study exhibited a remarkable ability to tolerate extended periods of drought. Despite receiving no supplemental irrigation, all four species established and grew substantially over the 18 months after they were planted in the landscape. In addition, *A. tridentata*, *H. microphyllus*, and *E. nauseosa* exhibited no visual indication of drought stress and retained their aesthetic value even as volumetric soil moisture declined below 10%. This reflects unique drought adaptions typical of many desert perennials, including morphological adaptations such as modified leaf structure, extensive or deep root systems, and drought dormancy (Chaves, Maraco, & Pereira 2003). All four species displayed rapid root growth exceeding 60 cm depth within one year of planting, surpassing the 15 – 30 cm average rooting depth commonly seen in non-xerophyte landscape ornamentals (St. Hilaire et al. 2008). This is particularly remarkable given that the soil at the study site was shallow and underlain by bedrock at 60 cm. Roots of the target individuals were observed penetrating small crack in the underlying bedrock. The rooting depths that our study species displayed in a modified urban landscape were similar to those observed in undisturbed natural landscape in the Owens Valley of California, U.S.A. (Mata-González et al. 2014). In addition to a deep and extensive root system, *R. cereum* also exhbited marked drought dormancy, losing most of its leaves during late summer and early autumn.

Landscape water requirement. Such drought tolerance adaptations are likely a large reason why the seasonal pattern of water potential and visual indicators of water stress did not track ET_{ref} or VPD_d. This lack of correlation between plant water demand and ET_{ref} complicates efforts to estimate irrigation demand in a landscape (Kjelgren 2016). Most currently available tools for estimating landscape water demand are modified versions of models that were originally developed for estimating water requirements in agricultural systems (Farag et al. 2011, Gober et al. 2011, Nouri et al. 2013). These models assume that water demand and evapotranspiration are closely correlated. A typical approach estimates water demand as a fractional proportion of ET$_{ref}$. The proportion is estimated using adjustment factors to account for species differences in water demand as well as a range of other processes and factors, such as microclimate, that potentially modify water flux from the landscape (Pannkuk 2010, Radwan 2010, Grabow 2013).

Table 3.2: Estimated change in above ground biomass (g) of four xerophyte plant species over 18 months planted in an unirrigated urban residential landscape in Bend, Oregon, U.S.A. Biomass estimates are presented for the replicated 10% reference unit and the derived total plant estimate. Values are means (standard deviation), n = 4. HODU = Holodiscus dumosus; ERNA10 = Ericameria nauseosa; ARTRW8 = Artemisia tridentata ssp. wyomingensis; RICE = Ribes cereum

Species	HODU	ERNA	ARTRW8	RICE
Reference unit (g)	6.0 (0.2)	7.6 (0.4)	6.6 (0.1)	7.1 (0.5)
Total plant (g)	60.03	75.55	66.25	70.50
1 gallon nursery stock	5.38 (0.4)	14.13 (0.9)	5.13 (0.2)	6.38 (0.4)
% increase	1020	434	1191	1005

However, the suitability of ET-based approaches for estimating the water demand of xeric vegetation is questionable (Mata-González et al. 2005). The extreme morphological and physiological adaptations to water stress that these species exhibit are likely not fully accounted for in the ET$_{ref}$ adjustment factors used in landscape irrigation models (Mata-González et al. 2005, Ferguson 1987, Smith and Smith 2013). We estimated irrigation scheduling recommendations for our study landscape using three widely available irrigation scheduling models: 1) Hunter Run-Time Calculator, 2) EPA WaterSense New Home Specifications, and 3) The Simplified Landscape Irrigation Demand Estimation (SLIDE). These models were selected because of their accessibility (e.g. on-line availability) and their wide acceptance in the landscape industry. Each model is based on ET$_{ref}$ but uses different species-specific adjustment values. Models also differ in the type and number of adjustment factors related to other parameters such as vegetation density. We parameterized the models based on 0.1 ha of landscaped area at the Desert Rain study site. Details and summary model calculations are available in (Martinson 2018). The three different models gave estimates of landscape water demand that ranged from 336.9 m^3 /season for WaterSense to 79.5 m^3/season for Hunter and 61.52 m^3/season for SLIDE. The different results largely reflect the water demand relative to ET_{ref} that each model estimated for xerophytic vegetation. Differences in water demand estimates across various models have been shown to largely reflect differences in plant or landscape specific adjustment factors to Et_{ref} (Kjelgren 2016). The results of our study suggest that even the low water demand estimates provided by existing models may overestimate demand for many extreme xerophyte species.

A significant constraint to improving the estimates made by water demand models is the lack of empirical data to parameterize them. However, ongoing research is beginning to provide empirical estimates of water use for common landscape types and species, at least for the Mediterranean climate zone of California (Snyder and Ackley 2015, Reid and Oki 2008, Reid and Oki 2016).

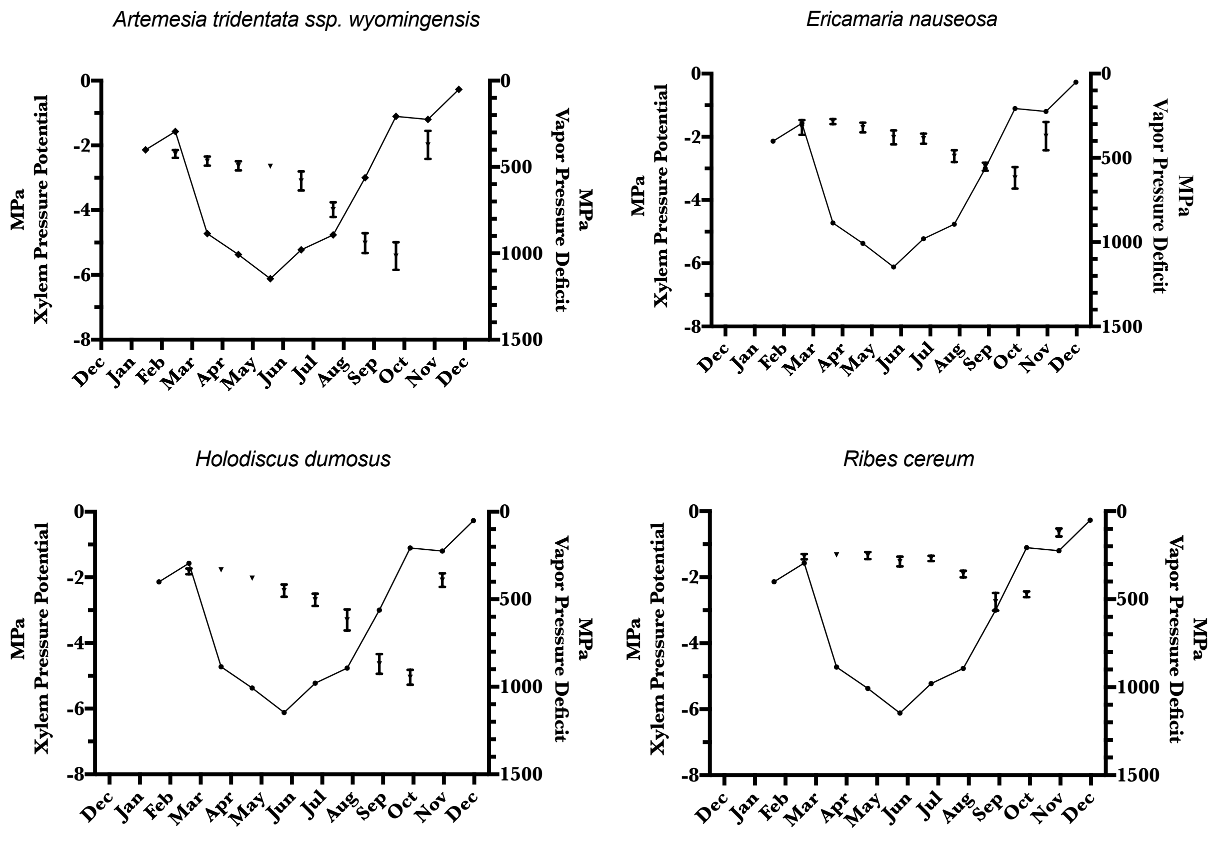

Figure 3.4: Monthly xylem water potential (symbols) over the course of a year for four xerophyte plant species in an urban residential landscape in Bend, Oregon, U.S.A. Vapor pressure deficit (VPD) is plotted as a solid line.

Urban landscapes. In created urban landscapes, severe disturbance associated with construction activities alters conditions such as exposure, soil compaction and chemistry, wind patterns, hydrologic function, and biotic communities, resulting in highly modified environments (Craul 1991, Lorenz and Lal 2009). These altered conditions could interfere with xerophyte drought adaptations. For example, increases in soil bulk density can negatively affect root growth through the rhizosphere by reducing pore space and the ability of soil to hold plant accessible moisture (Benbough et al. 2005). However, the species in this study performed similarly to those in less disturbed contexts. Rooting depth of the study species in the first year was unexpectedly deep given the shallow soils and rocky substrate. All study species developed fibrous roots exceeding 50cm, accessing consistently higher moisture levels at greater depths than normally expected in urban landscapes or designed for in urban irrigation systems. This might be a primary reason why the study species performed so well. Another reason is that soils at the study site were structurally similar to those at a nearby reference site, although soils at the study site were shallower. While bulk density has been shown to increase at construction sites (Evanylo et al. 2016), we found no statistically significant differences in bulk density between Desert Rain and the reference site.

Table 3.3: Representative soil properties across a depth profile (10-60cm) at an urban residential study site in Bend, Oregon U.S.A. (Desert Rain) and a nearby undisturbed reference site (Reference Site). Values are mean, with standard deviation in parentheses, n = 5. The Desert Rain site had shallow bedrock at 60 cm so soil properties could not be reported

	10 cm		30 cm		60 cm	
	Desert Rain	Reference Site	Desert Rain	Reference Site	Desert Rain	Reference Site
Bulk Density (g/cm^{-3})	1.05 (+/-0.19)	1.04 (+/-0.07)	1.27 (+/-0.23)	1.23 (+/-0.04)	---	1.39 (+/-0.13)
Soil Porosity (%)	0.60 (+/-0.07)	0.61 (+/-0.03)	0.52 (+/-0.09)	0.54 (+/-0.02)	---	0.47 (+/-0.05)

The specific construction techniques used at Desert Rain might be a reason for the for the relatively low bulk density. Site construction included extensive subsurface excavation for infrastructure unique to a Living Futures residence. The extent of the excavation exceeded levels commonly associated with residential construction, and may have decreased soil organic matter while mitigating soil compaction. Another mitigating factor is that the Desert Rain landscape was designed to emulate the structural and spatial characteristics of reference communities. The landscape included a diverse and purposely chosen association of plant functional types that included grasses and forbs. The physical facilitation and spatial patterning of these different components are known to be critically important to the ecological function of plant associations in semi-arid environments (Jackson and Caldwell 1993). Results of this study suggest designing and constructing urban landscapes within those parameters can result in similar functional aspects and ecological processes, such as hydraulic lift and nutrient cycling, and reduce landscape water use requirements.

Summary

Xerophyte species can be a suitable landscape choice in arid and semi-arid environments even in urban residential landscapes. However, current landscape management approaches will likely need to be adjusted to achieve the maximum water savings benefit from their use. Current water demand models will likely overestimate water demand in many instances because there is often no correlation between plant water demand and ET_{ref} for extreme xerophyte species. Also, conventional landscape management assumes an average shrub rooting depth of 150 – 300 mm (St. Hilaire et al. 2008), and models developed to encourage irrigation efficiency are based on average rooting depths, soil characteristics, and application efficiency of the irrigation system (Ferguson 1987, Hilaire et al. 2008, Irrigation Association 2014b, Nouri et al. 2013, White 2013, Connellan 2013, Jensen 2016). A constraint to developing better management guidelines for xerophyte species is that few studies have described their drought physiology in the context of ornamental landscapes. Additional work is needed to quantify drought stress response of most landscape species, most notably species with the aesthetic value and physio-biochemical adaptations that can contribute to a significant reduction of water use in urban landscapes.

Chapter 4 - Retrofiting a Residential Landscape Irrigation System to Improve Irrigation Efficiency in a Semi-Arid Environment: A Central Oregon Case Study

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Abstract. The efficient use of water in urban landscapes is a critical subject for many municipalities throughout the western United States. The distribution and allocation of water as a limited resource is becoming increasingly important as long-term drought conditions continue to affect the availability of water. Municipalities are responding these challenges by looking at options to reduce urban water consumption. Landscape irrigation is often a target of conservation efforts, but few case studies exist documenting the real potential of water savings using design considerations and technological advances in the irrigation industry.

This study quantifies actual outdoor water savings from retrofitting an existing commercial landscape irrigation system to a more water efficient design. This provided a unique opportunity to study the effects of irrigation system modification on outdoor water use in a realistic urban environment. We compare average annual landscape water use data collected by the city of Bend, Oregon at Summit Park, a commercial low-income housing development, with results of a redesign and modification of the existing irrigation system. We achieved a 44% reduction in irrigation water use through utilization of current available technology. Landscape maintenance decisions are discussed as factors contributing to decreased benefits of the irrigation system modification.

Key Words: irrigation, irrigation scheduling, urban landscapes, water-use efficiency

Introduction

Increasing demand for freshwater as well as supply disruptions have increased the frequency and spatial extent of water scarcity such that 4.0 billion people now experience severe water scarcity at least one month of the year (Mekonnen and Hoekstra, 2016). The World Economic Forum has cited the increasing frequency of water scarcity as one of the greatest systemic risks facing global society (World Economic Forum, 2017). These risks have spurred considerable interest in developing strategies to reduce consumptive water use and improve water use efficiency (Hoekstra, 2014). In urban environments, a particular focus of these efforts has been the water used to irrigate residential, commercial and public landscapes. This is because landscape irrigation accounts for a considerable proportion of residential water use, ranging 40 – 70% (Brookshire 2002, Mayer et al. 1999, Hilaire et al. 2008). Perhaps because landscape irrigation is the least valued use of water by many people (Stoutenborough and Vedlitz, 2014), it has been a focus of public concern as well as municipal regulation and policy development. This is particularly true in the western United States where long-term drought conditions have increased concerns over water availability in rapidly growing urban areas (Hornberger et al., 2015).

These municipal efforts take the form of a range of regulations, economic incentives, and educational outreach designed to reduce residential water use (Hess et al. 2017). Some of these policies, such as mandatory water use restrictions, don't prescribe specific actions; others are designed to directly foster the adoption of technologies and landscape designs that improve water use efficiency. These strategies usually focus on improving the efficiency of the irrigation system and on changing landscape designs to include more xerophytic or water efficient vegetation types. Although water conservation efforts are increasingly being implemented in urban areas, relatively few studies have quantitatively evaluated the actual water savings gained from adopting strategies under realistic conditions. The studies that do exist have been conducted in only a small proportion of the socio-economic and environmental contexts that exist in urban areas (Hogue and Pincetl 2015). In addition, city and region scale studies typically assess how broad policy changes such as water pricing influence water use patterns, but not how the adoption of specific practices alters water use efficiency. In some cases it appears that water use restrictions or negative incentives such as pricing drive reductions in water use without the adoption of water efficient practices. For example, when water use restrictions were imposed in southwestern Florida, USA annual landscape irrigation was reduced by 13%, but most users applied considerably less water than the required landscape water demand (Boyer et al. 2018). This suggests that in some cases day to day water management may not be well coordinated with the design of residential landscapes and irrigation systems, and this may interfere with the longer term functional goals expected of landscapes.

This case study quantified the change in water use that resulted from retrofitting an existing residential landscape irrigation system to a more water efficient design. The project was implemented at a low-income apartment complex in Bend, Oregon, USA. The retrofit process involved a detailed irrigation audit and subsequent design modifications to both the irrigation system and landscape plant composition, approaches that are commonly promoted as water conservation strategies. This provided a unique opportunity to study the effectiveness of these strategies at reducing landscape water use in a semi-arid urban environment.

Case study context and background

Project site characteristics. The project and study took place at Summit Park, a low-income housing complex covering approximately 2.1 ha in Bend, Oregon, a city of ~80,000 at 1,115 m elevation (44° 4’ 11.92” N, 121° 16’ 30.96” W). The climate is semi-arid and typical of the high desert region in the rain shadow of Cascade Range. Summers are typically warm and dry with an average daytime temperature of 25 ^{o}C (June – September). Winters are normally cold, with most annual precipitation falling as rain or snow. Average winter daytime temperature is 5.97 ^{o}C (November – February). Average annual precipitation is 289 mm (Figure 4.1).

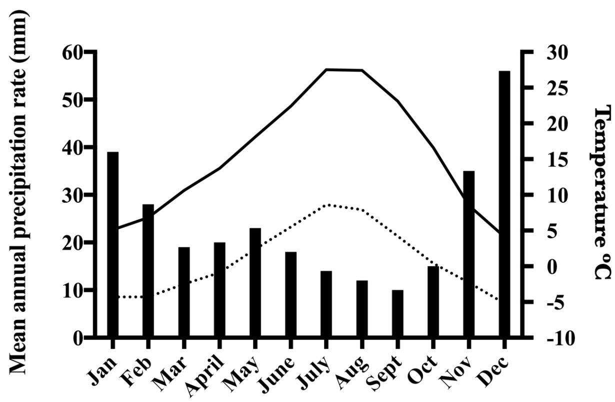

Figure 4.1: Climograph for Bend, Oregon U.S.A. Mean monthly precipitation (bars), mean daily high temperature (solid line) and mean daily low temperature (dotted line) are historical averages (1981 - 2010).

Summit Park is a public-private partnership. The city of Bend maintains ownership of the land and subsidizes a portion of the rent residents pay. A private developer owns the structures and manages the property for low-income residents (Bend 2015). The complex was originally constructed in the mid 1990's and includes 7568 m^2 of irrigated area: 6556 m^2 of turf and 1012 m^2 of planted shrub beds (Bend 2016). Sod covers most of the property outside the buildings. A one meter tall berm planted with a mix of conifer and deciduous shrub and tree species runs the length of the east side of the property. Two large berms (>2 meters tall) run north-south in a common area between two multi-unit buildings, and narrow planting beds with mature conifer shrubs exist along the foundation of each building that faces the parking area. The plantings on each side of the entry drive are predominantly lawn with planting beds of aspen (*Populus tremuloides*), redtwig dogwood (*Cornus sericeus*), barberry (*Berberis sp.*) and Oregon grape (*Mahonia aquifolium*). Sod composition on site consists of three grass species; *Lolium perenne, Poa pratensis,* and *Festuca spp* (Baker et al. 2014). Shrub beds are limited to small linear plantings between sidewalks and building foundations (Figure 4.2).

Figure 4.2: Summit Park Apartment Complex, Bend, Oregon. Note the extensive sod areas covering approximately 90% of the property. The letters on the buildings correspond to buildings referenced in the text. Source: Google Earth Pro, 2018.

Outdoor water at the site is uniquely metered separately from indoor use, providing detailed landscape water use data on a weekly basis. These data exist for the years 2011-2018 covering a period both before and after project implementation in 2015. Records provided by the city document a mean annual application rate over the five years prior to the implementation of this project (2011-2015) of 11.7 x 10^6 liters (Bend 2016). A formal irrigation audit of the site, which was not part of the present study, was completed by the city in 2013.

Project participants and goals. This project was initiated by the building owners as a way of reducing operating costs at Summit Park, primarily through a reduction of outdoor water use. The city supported the project by providing partial project funding, supplying water use data, and monitoring results. We provided planning, design, and implementation of the project as an opportunity to study results of the retrofit of the existing irrigation system.

The property owners identified a target reduction of 30% below annual outdoor water use, primarily in response to results of the 2013 audit which documented excessive water use, but also in reply to city pressure to reduce outdoor water use. The initial vision for achieving this goal involved improving both the efficiency of the irrigation system as well as converting a significant proportion of the landscape from relatively high water use species to low water use types modeled on local high desert plant communities. However, as we describe below, budget constraints forced modifications to the original design concept. The plan that was implemented was designed to achieve the majority of target water use reductions through improvements in irrigation system efficiency, although replacement of high water use plants with native xerophytic species was completed for approximately 10% of the site. In addition, modifications to site topography were incorporated in an effort to retain more stormwater on site.

The project included four distinct steps: 1) an irrigation audit, 2) review of audit results and retrofit design development, 3) design implementation, and 4) monitoring.

Retrofit design and implementation

Irrigation audit. An irrigation audit is a procedure used to collect information about the efficiency of an irrigation system (Wilson 2009, Irrigation Association 2014b). In 2015, a formal irrigation audit was performed on the existing site irrigation system. The audit was completed by a certified landscape irrigation auditor adhering to guidelines developed by the Irrigation Association (IA). The audit included a visual inspection of the irrigation system and a determination of the applied irrigation precipitation rate – the amount of water emitted from an irrigation nozzle through specifications provided by the manufacturer.

The irrigation audit identified 18 separate irrigation zones, 17 of which were functional. Each zone contained a variety of irrigation heads, nozzle sizes, and precipitation rates. Thirteen zones were identified as irrigating turf, two were identified as shrub zones, and three were mixed turf and shrub beds. The audit also showed that the system was not a unified design. System elements were inconsistent and included a mixture of different irrigation head types, nozzle types and sizes, as well as redundancies in head placement. The existing sprinkler heads were also of older relatively less efficient designs. In addition, the system had several broken or leaking irrigation control valves. The system appeared to have been modified over time, with multiple heads irrigating the same area on multiple schedules, and a variety of head types by different manufacturers installed on the same irrigation zone.

The rate of water delivery varied considerably both across zones as well as within zones across scheduled irrigation run times (Figure 4.3). This spatial and temporal heterogeneity in water application rate was a significant source of system inefficiency. Calculations completed as part of the audit indicated that replacing sprinkler bodies and heads with a uniform more efficient head design would result in an expected 51% decrease in total annual water use at the site.

Retrofit design. The system retrofit focused on three primary areas: 1) improving the irrigation precipitation rate and distribution uniformity through standardizing nozzle types, updating to more efficient irrigation head designs, and improving the spatial patterning of irrigation heads; 2) addressing grading concerns and improving onsite storm water retention; 3) replacing some of the high water use vegetation with native xerophytic species. Budget constraints were a significant consideration in the design process. These constraints shaped the project design in two significant ways. First, to affect the most change within budget constraints, the existing irrigation zones were prioritized in terms of their inefficiency. Only zones that were

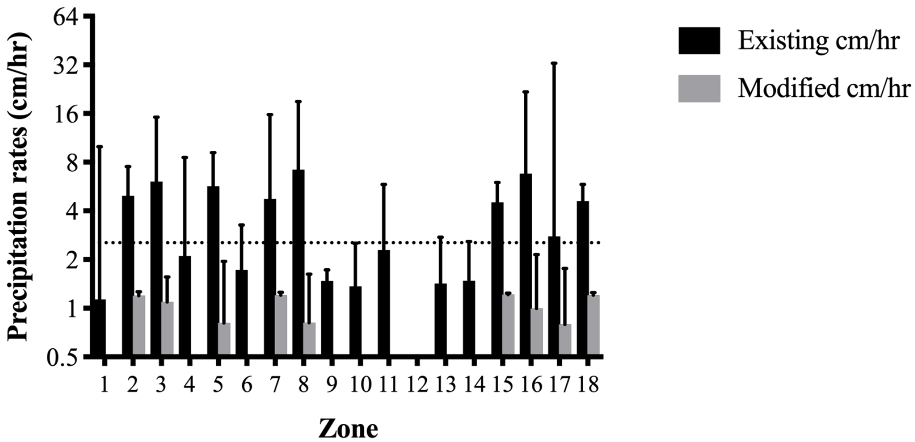

Figure 4.3: Irrigation precipitation rates recorded for 18 irrigation zones before and after system modification at the Summit Park residential complex, Bend, OR USA. Black bars are the mean (deviation) precipitation rate before modification determined by an irrigation audit in 2015; gray bars are mean (deviation) precipitation rates following system modification. Because of budget constraints system modification were only implemented in zones with a mean rate exceeding 2.54 cm per hour (dotted line). Zone 12 was a nonfunctioning existing zone and was not considered in our analysis.

identified as exceeding a mean precipitation rate over 2.54 cm per hour were retrofitted (Figure 4.3). Secondly, early designs called for replacing 90% of the existing vegetation with xerophytic native species. However, budget constraints forced most of these plans to be scrapped. Instead, only about 10% of the site was replaced with xerophytic species. These were included as part of the stormwater management aspect of the design.

We reviewed precipitation rate data for each head in each of the priority zones and recommended changes in irrigation body type, nozzle size, or head location to increase application efficiency. Consistency in spatial coverage was addressed through adjusting irrigation head placement or removing redundant or ineffective heads. In some cases, the spatial distribution of heads was adjusted to optimize the coverage patterns of the replacement head. Irrigation precipitation rates were made more temporally uniform by using consistent head and nozzle designs throughout the system. The variation in water pressure inherent in long irrigation runs was mitigated through the use of pressure regulating irrigation bodies.

Another factor affecting irrigation efficiency is the hydraulic conductivity of the soil. Application rates that are too rapid given the hydraulic conductivity can result in considerable runoff and poor absorption into soil. Saturated hydraulic conductivity (Ksat) quantifies the potential for subsurface infiltration and are useful when designing irrigation systems for deeply rooted species (Watt, Vincent and Dravid 1995). Ksat values were completed for a depth of 60 cm to determine the ability of soils at Summit Park to provide plant available moisture at deep soil layers, and ranged from 26.7 to 92.0 µm/sec.

A significant aspect of the retrofit design was to replace the existing spray heads with a newer, more efficient design. Sprinklers can be the most important aspect of overall system efficiency (Darko et al. 2017). Several newer sprinkler designs have been commercialized based on low flow rate, multi-stream rotational spray heads. These designs produce more uniform spatial coverage and allow for better absorption into the soil compared to other designs such as fixed spray head (Solomon et al., 2006). The heads used in this project were MP Rotators™. MP Rotators are trademarked by Hunter Corporation and feature a multi-trajectory rotating stream system delivering multiple streams of water at a steady rate. Reported efficiency rates of MP Rotators is 80% (water loss to evaporation and atomization account for 20% water loss from each head), with a consistent application rate of 9.9 mm per hour (Hunter 2016). This is lower than reported Ksat values for soils in the project site (9.9mm/hr = 2.75 µm/sec), indicating that application rates will not exceed infiltration.

Each target zone was designed and modified individually based on the audit analysis. For example, Zone 16 is representative of an average precipitation rate in the study area. Prior to modification, this zone included 23 individual irrigation heads by three manufacturers with 10 different nozzle sizes applying a total of 127 liters per minute. Replacing these heads with pressure regulating bodies and MP Rotators sized and spaced for the specific application radius of each head resulted in a total precipitation rate of 49.3 liters per minute, a 61% decrease in precipitation rate for that zone (Figure 3). In some cases, recommendations were not adopted in the final plan because underlying geology prevented moving pipe or because of budget constraints.

Storm water capture and reuse was improved through grading changes that created small swales in each shrub bed immediately adjacent to interior facing residential units (Units A – J, Figure 4.2). All roof runoff was directed to swales, and all spray irrigation within the shrub beds was changed to 13 mm in-line drip system (Netafim ™) with 1.8 liter/hr emitter rates at 46 cm spacing. Existing vegetation was removed and replaced with native xerophytic shrub and forb species.

Irrigation scheduling. Irrigation at Summit Park is currently controlled by a manually adjusted timer that controls the valves necessary for each irrigation zone to disperse water. Generally, an irrigation schedule is developed that defines the time of day and duration of run time for each zone of irrigation. At Summit Park, that schedule is entered manually, and seasonal adjustments must be entered monthly. However, newer control technologies typically include automatic adjustment in response to weather patterns and seasonal changes in ET rates. Maintenance guidelines submitted after completing the system retrofit recommended installation of a controller with the capability of automatically adjusting to instantaneous uploads of reference evapotranspiration (ET_{ref}), but that recommendation was not adopted.

Various irrigation scheduling models have been developed to assist in maximizing irrigation efficiency in urban landscapes. Many are created by irrigation suppliers or industry professionals, but several are city, state, or federal efforts. All are based on reference evapotranspiration rates (ET_{ref}). A typical approach estimates water demand as a fractional proportion of ET_{ref}. The proportion is estimated using adjustment factors to account for species differences in water demand as well as a range of other processes and factors, such as microclimate, that potentially modify water flux from the landscape (Pannkuk 2010, Radwan 2010, Grabow 2013).

At Summit Park, the reference ET rate for the month with the highest evaporative rate (July) is 188.98 mL/month. The equation used by the City to determine recommended irrigation rates modifies this figure with an adjustment coefficient of 0.83 to achieve a target reduction of 17% in irrigation water use, resulting in a modified base rate of 156.85 mL/m^2. This figure represents the estimated landscape water demand for each m^2 and is used to develop an irrigation schedule designed to apply that quantity of water per m^2/month. However, best management practices suggest seasonal adjustment of irrigation rates to reflect changes in monthly ET_{ref} values (Table 4.1). The irrigation schedule developed as part of this study for Summit Park adopted the use of seasonal adjustments.

Water use results

In 2016, the year after the retrofit was implemented, annual irrigation water use was 38.0% less than in pre-retrofit 2015. Over the first three years' post-retrofit annual irrigation water use was an average 34.4% less than the average over the previous three years (Figure 4.4). This reduction met the benchmark goal of a 30% reduction in outdoor water use. However, it fell short of the anticipated 51% reduction in average water use predicted to occur as a result of the system design changes.

Table 4.1: Designed monthly irrigation schedule for the irrigation retrofit of the Summit Park residential complex, Bend, Oregon. The schedule was developed using an evapotranspiration (ET) based model that estimated monthly irrigation demand by adjusting ET_{ref} using a landscape coefficient (K) and a month specific seasonal adjustment. ET_{ref} was the long-term average July ET, the month of peak plant water demand in the region; ET_{ref} = 188.98 mL per month; K = 0.83, which is the recommended value from the city of Bend.

Month	IA Adjustment	Volume after adjustment (ml/m2)	Monthly volume per m2 (liters)	Monthly L/ha
April	46%	86.93	869.31	8693.08
May	66%	124.73	1247.27	12472.68
June	79%	149.29	1492.94	14929.42
July	100%	188.98	1889.80	18898.00
Aug	89%	168.19	1681.92	16819.22
Sept	60%	113.39	1133.88	11338.80
Oct	34%	64.25	642.53	6425.32

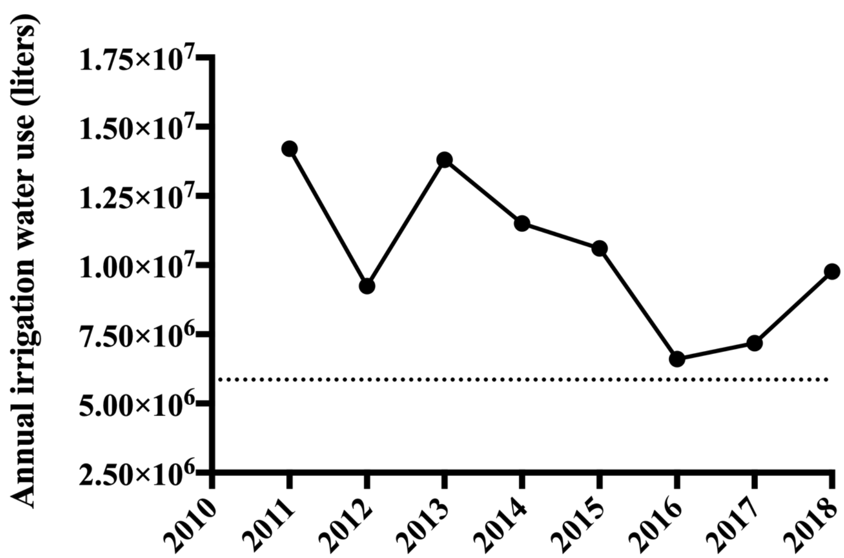

Figure 4,4: Annual outdoor water use before and after an irrigation system retrofit at the Summit Park residential complex, Bend Oregon. System design changes were implemented in September 2015. A formal irrigation audit was conducted in 2013 but was not associated with any irrigation system modifications. The dotted line indicates the annual irrigation rate recommended by the City of Bend. Source: City of Bend Public Works 2018.

The failure to meet the designed system potential appears to have been largely related to the manual aspects of irrigation scheduling. Detailed weekly water use records for 2018 indicate that irrigation scheduling was not adjusted to account for seasonal changes in water demand.

(Figure 4.5). Instead, the system was turned on at the start of spring and set to levels reflecting peak summer water demand. Previous years exhibited unexplained variation in year to year water use. Irrigated water use at the site had declined in the previous two years (2014, 2015) prior to the implementation of the retrofit. The reason for this is not clear, but it intriguingly occurred after a formal irrigation audit was conducted in 2013. Overall, the year to year variation in water use does not correspond to the yearly variation in estimated water demand. This suggests that manual alterations to irrigation scheduling were not accurately reflecting landscape water needs. We do not have an explanation for the precipitous drop in irrigation water use reported in 2012. It could reflect management decisions, but monitoring equipment error is also a possibility.

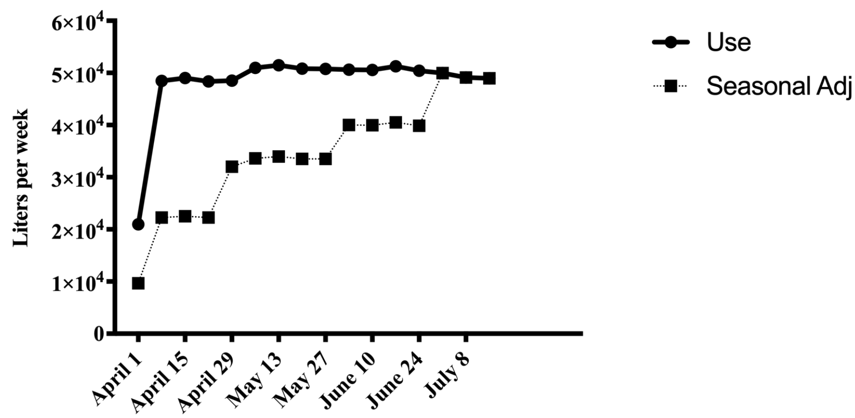

Figure 4.5: Weekly irrigation amount from April 1 through the week of July 8, 2018 at the Summit Park residential complex, Bend Oregon. The solid line indicates the weekly volume (L) of water applied at the site as recorded by the city of Bend. The dotted line indicates the planned irrigation schedule following seasonal adjustment recommendations from the Irrigation Association's Best Management Practices. Recommendations call for irrigation to supply 100% of ET_{ref} in July, the month of peak water demand at the site. The steady application rate (solid line) suggests a "set it and leave it" maintenance practice.

Discussion

The Summit Park project was designed to achieve a minimum reduction of 30% in seasonal outdoor water use. We exceeded expectations by achieving a 44% reduction from the 2011-2015 mean documented by the City of Bend. Although the project included some small modifications to the landscape plant composition and topography, the majority of these water use savings were achieved through improving the functional efficiency of the existing irrigation system. The retrofitted system delivered water more uniformly in space and time and at rates that improved water infiltration into the soil. Models and experimental studies indicate that uniformity and application rate are two of the most important factors influencing the application efficiency of landscape irrigation systems (Hilaire et al. 2008). However, there is considerable evidence that the majority of existing residential irrigation systems have fair to poor spatial uniformity (H. Solomon et al. 2006).

The patchwork nature of the pre-retrofit system at Summit Park suggests a history of piecemeal adjustments and poor system maintenance, factors that are likely widespread and common for established residential systems. In addition, the initial system at Summit Park was installed in the mid 1990's before more efficient multi-stream rotational spray heads were widely available and promoted. The results of this study suggest that periodic irrigation audits followed up with relatively modest but system orientated adjustments can result in significant water savings. A few other studies have reported similar results. Nevada residents that participated in a program to replace fixed pop-up spray heads with multi-stream rotational spray heads improved their average lower quarter distribution uniformity (DU_{LQ}) from 0.40 to 0.58 (Sovocool, Morgan and Drinkwine 2009). Solomon et al., (2006) audited irrigation systems at 29 sites in the western U.S. and retrofitted them with multi-stream rotational spray heads. The DU_{LQ} of the systems improved from 0.44 to 0.70, which translated into a water savings potential of 22% - 40% relative to the pre-retrofit systems.

Irrigation scheduling also has a significant influence on the water efficiency of residential landscapes. There is evidence that the actual amount of irrigation water applied in residential landscapes frequently does not match landscape water demand (Endter-Wada et al. 2008, Salvador, Bautista-Capetillo and Playán 2011, Romero and Dukes 2014). A key factor influencing this variation appears to be how human irrigation managers interact with the irrigation system, particularly its degree of automation (Endter-Wada et al. 2008). Systems that automate the operating schedule but that still require user input to adjust water delivery to match actual landscape water demand are susceptible to overwatering errors. Landscapes that are watered by manually operated systems generally receive lower amounts of water compared to similar landscapes watered by schedule automated system controllers (Syme et al. 2004, Endter-Wada et al. 2008). This pattern even exists in cases were landscape management is provided by a professional landscape maintenance service and in institutional settings with in-house grounds crews. For instance, Utah elementary schools that have schedule automated irrigation control systems generally experience high landscape water use exceeding landscape demand, while schools with manual systems have generally low water use that meets conservation targets (Kilgren et al. 2010). Schedule automated controllers seem to foster mistakes or complacency even when users are knowledgeable about patterns of landscape demand. In the Utah school study (Kilgren et al. 2010), many of the schools that had schedule automated controllers continued to have overwatering issues even when they were provided an ET based irrigation schedule and training to implement the plan. In contrast, many of the schools that had manually operated systems achieved reductions in water use after training even though they were already starting at a low water use base. Something similar happened in this case. Although the retrofit design included an irrigation schedule that made seasonal adjustments based on historic site ET, the plan was not implemented. This resulted in an average application rate 27% higher than would have been applied with seasonal adjustment of the irrigation schedule (Figure 4.5).

One potential solution to this issue is the more widespread adoption of *smart* controllers that automatically adjust irrigation delivery to local water demand. These controllers typically use near real-time data from site based sensors or remote data streams to parameterize landscape water demand models using software. The installation of smart controllers can significantly reduce residential irrigation at sites with a history of irrigating in excess of landscape water demand (Davis and Dukes 2015). However, smart controllers by themselves are not a panacea. Although smart controllers typically achieve 40% to more than 70% reductions in water use under controlled experimental conditions, average savings are considerably less when they are deployed in actual residential settings (Dukes 2012). This partly reflects issues related to training and maintenance of the systems, but it also reflects the highly variable pattern of urban outdoor water use. For example, the installation of smart controllers can increase landscape water use for users who have historically irrigated below water requirement as estimated by the particular model used by the smart controller (Mayer et al. 2009). In addition, many of the water demand models used in commercially available smart controllers are ill-suited to estimating the water demand of landscapes dominated by xerophytic vegetation. For example, ET based models systematically overestimate water demand for several regionally native shrub species within a residential landscape located near the Summit Park site (Martinson et al. In-Press).

A range of socio-economic factors also likely influence variation in landscape water use that is independent of irrigation system design. Continued drought conditions in much of the western U.S. has stimulated the development of both restrictions and incentive programs aimed at reducing water use in urban landscapes (Shandas and Hossein Parandvash 2010, Hilaire et al. 2008). These often take the form of scaled pricing for water; costs per unit increase with the volume of water used, or watering frequency restrictions (Brookshire 2002). The decision to improve water use efficiency is frequently made by owners or managers who are responsible for fiscal oversight but who have little experience or knowledge about how best to implement changes in ways that will reduce water use but that sustainably maintains the functional goals they have for their landscape. They also lack the capacity to monitor and adaptively manage the system. Professional landscape maintenance contractors could help fill this knowledge gap by properly implementing plans, maintaining systems, and providing active troubleshooting and decision management. However, many landscape management companies have little or no incentive to monitor use or to provide expert water management support. This gap between intent and implementation is a substantial barrier to addressing long-term water use concerns in managed landscapes. But there are no easy solutions. Companies providing landscape maintenance at Summit Park have changed three times since 2015 (Wooden 2018). The lack of consistency in maintenance can result in large swings in water use, and may be a factor contributing to the significant variation in water use documented at Summit Park in 2012 (Figure 4.4). Although the city has an active program in "waterwise" landscaping, involvement in that program is voluntary and the adoption of recommendations developed through the program by landscape maintenance companies is unknown (Buettner 2018). The responsibility to educate maintenance companies on current water use issues and irrigation scheduling is often left to homeowners or property managers. How project goals and guidance about the new system was to be communicated with landscape maintenance personnel was not an explicit part of the Summit Park project plan. As a consequence, the role of communicating with maintenance workers oscillated between the city's Department of Public Works, the property owner, and the retrofit design team, resulting in a general lack of understanding by maintenance workers of the intent and design of the modified irrigation system.

In their defense, landscape maintenance companies are expected to preserve a level of aesthetic value critically important in urban landscapes (Hayden 2015), and reducing water use often generates questions of aesthetic value. Although aesthetics is a subjective value (Thompson 2000, Thorne and Huang 1991, Tyrväinen et al. 2003), the appearance of a healthy landscape is the primary goal of most landscape maintenance companies. Maintenance practices designed to meet that goal often include the application of water at rates exceeding plant physiological requirements (Martinson et al. In-Press), or base irrigation schedules on experience or intuition (Harris et al. 2012) and fail to consider the effect on long-term water conservation objectives.

The modification of the irrigation system at Summit Park documents the potential for increasing irrigation efficiency and reducing water use through careful design and application of existing technology. However, maintenance practices have the potential to significantly affect the degree of success in efforts to reduce landscape water use, identifying a need for consistency in educational opportunities for landscape contractors and maintenance companies. The development of educational programs targeting outdoor water use reduction in response to growing concerns over long-term drought and water availability in the western United States must address regional environmental conditions, be responsive to local values, and be collaborative between municipalities, the landscape industry, and educational institutions.

Appendix A

Irrigation Model Analyses: Desert Rain

We tested three on-line irrigation models commonly used by the landscape industry to determine annual water savings from the design and installation of an unirrigated landscape at Desert Rain, a home and compound constructed in the semi-arid environment of Bend, Oregon U.S.A. (44^{o} 3’ 10.87” N, 121^{o} 19’ 17.67” W). Environmental variables reflecting site specific environmental conditions were entered to the degree that each model allowed modification of environmental parameters. Two models, Hunter and WaterSense, include options for specifying general irrigation type (i.e. drip, spray, rotor); the third model, SLIDE, did not include that option.

Each test assumed a 31-week irrigation season, typical for the high desert environment of Bend, Oregon. Reference evapotranspiration (ET_{ref}) figures reflect the month with the highest historic rate; July, at 7.44 inches. Model results are based on each 1000 square feet, but extrapolated to include the entire 11,328 ft^2 of landscape area.

Hunter Runtime Calculator

Hunter Industries is a producer of landscape irrigation, lighting, and control equipment, and one of the primary landscape irrigation supply companies in the United States. The company website states that a primary goal is to improve resource conservation in the landscaping industry. The Runtime Calculator was designed to address a company goal of resource conservation through efficient irrigation using Hunter specific products.

Methods

We entered site-specific environmental parameters into the on-line Hunter Runtime Calculator to assess realized water savings at Desert Rain. The model allows input of six parameters (slope, wind speed, soil type, exposure, plant density, plant type) to modify reference evapotranspiration (ET_{ref}). Users are also offered a choice of Hunter-brand irrigation system products with various application and efficiency rates.

For this study, we entered the mean ET_{ref} rate of 7.44 inches for July (reference month), “slight” slope (3-5%), sandy loam soils, “high” exposure (6-8 hours of sun per day), “moderate” density (1/2 to 2/3 ground shaded), and drought tolerant plants (Table A1.1). We selected the Professional Landscape Dripline (PLD) with 0.4 gallon per hour (GPH) in-line, pressure-compensating emitters at 18 inch spacing for its high (85%) efficiency rate (Hunter Industries 2018). Spacing between irrigation lines is entered at 18 inches. Technical specifications state this spacing and application rate provides a precipitation rate of .29 GPH. The model automatically selects a crop or landscape coefficient (K_c) of .35 for drought tolerant plants. This parameter is not adjustable in the current model. The irrigation system was analyzed for three wind speeds: high, medium, and low.

Results

Summary recommendations include irrigating one day per week, with three run times for that day. Analysis of recommendations for three wind speeds (high, medium, low) resulted in a mean irrigation quantity of 1.5479 gallons per day (Table A1.2). Wind speed was the only environmental variable ($K_{microclimate}$) modified during our trials.

A 1000 ft^2 area would require 441 emitters (21 lines x 21 emitters @ 18" spacing) for a total of 47.985 gallons/season/1000 ft^2. This figure reflects an ET rate of 7.44 and a K_c value of .35. The K_c rate is appropriate for standard irrigation scheduling practices for xeric vegetation when the maximum allowable depletion of soil moisture (MAD) is assumed at 70%.

Converting irrigation recommendations of inches/day to gallons/day/area utilizes the following equation:

$$gal\ per\ day = \frac{IRm/d}{60} \times \frac{in/hr}{231}\ x\ e \qquad [1]$$

Where IRm/d is the recommended irrigation run time in minutes per day, in/hr is inches of water per hour, and e is number of emitters per unit area at a specified spacing. Volume of water output for each recommended run time was calculated per 1000 ft^2, and totaled for a 31-week irrigation season.

The unirrigated portion of the landscape at the study site is approximately 11,328 ft^2. Estimated average annual water savings utilizing PLD is 543.57 gallons per emitter for a total potential water savings of approximately 21,161 gallons (based on 441 emitters/1000 ft^2).

Seasonal adjustment following Irrigation Association recommendations modifies the figures in response to monthly changes in precipitation, humidity, and temperature. Seasonal adjustment results in a total potential water savings of 7,821 gallons per 1000 ft.2; a total of 88,526 gallons for the entire study area at Desert Rain.

This model resulted in a 64% reduction in water use compared with the seasonally adjusted base rate (IA).

Table A1.1: Environmental parameters and irrigation type entered into the Hunter Runtime Calculator. The parameters entered reflect actual conditions at the study site. PLD = Professional Landscape Drip. GPH = Gallons per hour.

Variable	**Entered**	**Specified**
Vegetation type	Drought tolerant	
Sprinker type	In-ground drip system (PLD). Emitter spacing @ 18”, row spacing @ 18”	Drip (PLD @ 0.4 GPH)
Emitter spacing	18”	
Row spacing	18”	
Vegetation density	Moderate, 1/2 to 2/3 ground shaded	
Exposure	High, 6-8 hours of sun/day	
Wind	The effects of three wind speeds were analyzed	Low, med, high
Soil type	Sandy loam	
Slope	Slight, 3-5%	

Table A1.2: Hunter Runtime Calculator recommendations for Professional Landscape Drip (PLD) irrigation system. Runtimes vary by wind speed (increased transpiration rates). Model recommendations are presented in inches per hour. All figures are converted to gallons per day, averaged, and the mean value used to calculate annual water savings per 1000 square feet at the study site.

Wind Speed	Run time (Hrs/day)	Inches (gal) hr/emitter	Gal per 1000 ft^2 /day @ recommended runtimes
Low	2.1	.29 (.0026)	1.167
Med	2.75	.29 (.0026)	1.528
High	3.25	.29 (.0026)	1.808
Mean			1.501

$$1.501\ (mean) \times 31\ weeks = 46.531\ gallons\ per\ season\ per\ 1000ft^2$$

$$46.531 \times 11.328\ =\ 21{,}161\ gallons\ per\ season$$

EPA WaterSense New Home Specification

Water Budget Tool (V 1.02)

The Environmental Protection Agency provides an irrigation budgeting tool targeting landscape contractors working on WaterSense certified new construction. The format is an Excel spreadsheet in which designers enter basic site conditions to modify reference evapotranspiration (ET_{ref}). Specific requirements and minimum standards apply if the project is going to be considered for certification under the WaterSense program. To be certified, the site must achieve a minimum 30% reduction from 100% reference ET of the peak watering month. The model develops a Baseline figure reflecting 100% ET_{ref} utilizing the following equation:

$$Baseline = ET_{o(ref)} \times Area \times C_u \qquad [2]$$

Where ET_o is the reference ET rate for the peak watering month, area is the irrigated area in ft^2, and C_u is 0.623 – a conversion factor resulting in gallons per month. The model determines a Landscape Water Allowance (LWA) as 70% of baseline, a 30% reduction from 100% reference ET, as a target for water reduction.

$$Baseline = 7.44 \times 1000 \times 0.623 = 4{,}635\ gallons\ per\ month\ per\ 1000\ Ft^2$$

$$4{,}635\ gallons\ per\ month \times 11.328\ (total\ area) = Baseline\ 52{,}505\ gallons\ per\ month$$

[3]

$$Landscape\ Water\ Allowance\ (LWA) = 0.70 \times Baseline \qquad [4]$$

Methods

We entered five environmental parameters into the Excel model, including reference ET (ET_{ref}) for the peak watering month, average precipitation rates for that month, the general type of vegetation being installed (low-water shrubs), area, and the basic type of irrigation being installed (Table A1.3). The number of environmental variables available for modification in the WaterSense model is lower than the Hunter model we tested, but greater than the SLIDE method.

Several variables are assumed based on inputs: 1) K_L (landscape) coefficient is automatically selected by shrub type. In this case, the K_L coefficient is set by the model at 0.2 for low-water shrubs; 2) A pressure compensating drip system is assumed to have a 90% distribution uniformity regardless of soil type. No option to input soils, spacing, or emitter flow rate exists in this model; 3) Plant density and microclimate conditions are assumed average.

Table A1.3: Site specific options entered for net water savings potential at the study property. The ability to enter environmental parameters for this model was lower than other models we tested, and several potential variables are automatically calculated by the software.

Variable	**Entered**
Area	1000 ft^2
ET_o (July)	7.44 in
Mean historic precipitation for reference month	.24 in
Vegetation type	Low-water Shrubs
Irrigation type	Pressure compensating drip

The WaterSense model provides recommendations for gallons per month. Entering site specific characteristics resulted in a monthly landscape water requirement of 989 gallons per month per 1000 ft^2 (approximately 247 gallons/week) based on a peak historic ET rate (July) of 7.44 inches. Since the WaterSense method is designed to target a thirty percent reduction in base irrigation volume for certification purposes, results simply state the calculated percent water use savings expected per season. Our analysis resulted in a 79% reduction in water use from the calculated baseline. Total estimated annual water savings for the project under this model is 7,664.75 gallons per 1000 ft^2: a total of 86,826 gallons for the entire project area for a 31-week irrigation season.

$$\left(\frac{989}{4}\ x\ 31\right) \times 11.328 = 86{,}826 \qquad [5]$$

Simplified Landscape Irrigation Design Estimator (SLIDE)

University of California, Center for Landscape and Urban Horticulture

Researchers at the University of California developed the Simplified Landscape Irrigation Design Estimator (SLIDE) method as a simple, useable alternative to models requiring subjective adjustment of plant and environmental adjustment factors (K coefficients). Kjelgren et al., (2016) describes SLIDE as "a sound basis for water conservation regulations that puts design, installation, and management of water efficient urban landscapes within reach of stakeholders." The basis of SLIDE is the estimation of water demand based on reference evapotranspiration (ET_{ref}) and defines a single adjustment factor for broad plant types rather than selectable ranges for plant, microclimate, and plant density coefficients common in other models.

The SLIDE “rules” (Kjelgren 2016) recognizes the effects of modified physiology and leaf morphology of desert plants on transpiration rate and water use requirements, and recommends a plant factor (PF) of 0.3 for xerophytic shrubs and forbs and 0.5 for desert adapted trees, although drought tolerant traits of desert adapted species would need to be addressed on a situational basis. Our analysis utilizes the recommended 0.3 Plant Factor for the mixed shrubs/forb landscape installed at Desert Rain.

The basic SLIDE equation is:

Landscape Water Demand (LWD (gal)) = $ET_{ref} \times PF \times LA \times 0.623$ [6]

Where ET_{ref} is the average reference evapotranspiration rate for the month with the highest value (July), PF is the plant factor associated with the broad type classification in SLIDE, and LA is the target landscape area in square feet. The 0.623 conversion factor converts inches of water to gallons of water

Methods

We entered 7.44 as ET_{ref} for the peak watering month (July) and the recommended plant factor (PF) of 0.3 for desert adapted shrubs. Landscape area (LA) = 1000 ft^2. Results indicate the Landscape Water Demand (LWD) in gallons per 1000 square feet of landscaped area per month at 1,390.54 gallons.

$$LWD\ (gal) = 7.44 \times 0.3 \times 1000 \times 0.623 = 1{,}390.54 \qquad [7]$$

The study site is approximately 11,328 ft^2.

$$1{,}390.5 \times 11.328 = \frac{15{,}752\ gallons\ per\ month}{4\ weeks\ per\ month} = 3{,}938\ gallons\ per\ week \quad [8]$$

$$3{,}938\ gallons\ per\ week \times 31\ weeks\ (ave.\ growing\ season) = 122{,}078\ gal.\ per\ season$$

[9]

Monthly adjustments (Water Balance)

Best Management Practices (BMP) developed by the Irrigation Association (IA) include recommendations for monthly adjustments of irrigation rate based on a percentage of reduction in ET from the month with the highest water use. The recommended adjustments reflect climatic conditions in broad biogeographic regions of the United States and have been adopted as a standard by the irrigation industry.

We applied water balance percentages to the results from each model to assess water savings of the Desert Rain landscape following irrigation industry best practices. The Hunter model resulted in irrigation recommendations 64% below a base rate calculated from historic reference ET, the EPA model resulted in a 79% reduction, and the SLIDE model recommended irrigation rates 70% less than historic reference ET (Figure A1.1). When the model results were compared to 2016 ET rates (U.S. Bureau of Reclamation), the Hunter model resulted in a 66% decrease from the base rate, the EPA model resulted in a 76% decrease and the SLIDE matched the 66% reduction from the base rate (Table A1.4). Utilizing the water balance percentages results in recommendations more closely adhering to irrigation Best Management Practices (Figure A1.2), although many landscapes in the western U.S. fail to consider water balance adjustments in irrigation scheduling (Buetner 2017).

Table A1.4: Mean water saving per 1000 ft^2 at Desert Rain based on the reference month (July) following seasonal adjustments modifying recommended irrigation volume by a monthly percentage reflecting monthly changes in ET rate categorized by broad biogeographic region (Irrigation Association, 2017). Figures for Historic ET represent average evapotranspiration rates from 1983 through 2015; figures in the 2016 ET column represent savings based on actual ET rates for 2016 (AGRIMet, 2017). Percentages indicate average water savings for a typical 31-week irrigation season per 1000 ft^2 at Desert Rain. The gallons of water represent actual annual water savings at Desert Rain based on each model. For example, the EPA WaterSense model resulted in the lowest water use recommendation of the three models tested, therefore the volume of water saved is the lowest of all models.

Model	Historic ET (gallons)	2016 ET (gallons)
Hunter	64% (7,821.00)	66% (8,342.79)
EPA WaterSense	79% (4,687.86)	76% (5,931.72)
SLIDE	70% (6,593.34)	66% (8,342.79)

Summary

We hypothesized that greater specificity in plant type, environmental variables, and irrigation materials would result in water use recommendations more closely tied to actual water requirements of a created landscape, but found no statistically significant differences between water volume estimation of the three models reviewed (r=1.0). All models utilized reference evapotranspiration rates (ET_{ref}) as the base for determining landscape water requirements, but differed in the use of coefficients modifying reference ET rates. The Hunter model offered the greatest specificity in environmental and materials variables, but resulted in the highest recommended water use requirement. The EPA's WaterSense model included similar options at a detail less robust than the Hunter model, but resulted in the lowest recommended landscape water use requirement. The SLIDE model resulted in volume recommendations between those of Hunter and WaterSense, even though it relied on a single coefficient reflecting broad plant types loosely associated with physiographic regions of California.

The models we tested represent two divergent approaches to determining landscape water demand. A broad, ecoregional approach is utilized by the SLIDE in classification of common landscape species and development of a modifier reflecting professional opinion about plant/water relations in specific physiographic regions of California. The Hunter and WaterSense models utilize site specific environmental conditions in addition to the type of irrigation and a modifier selected by the software for general plant types (i.e. drought tolerant). Each approach relies on reference evapotranspiration as the primary driver of landscape water use but differs in the level of complexity. In addition, the SLIDE model recommends modifying reference evapotranspiration by estimated water use requirements of individual species, although the method of determining the average coefficient of all plants in a landscape is unclear. The Hunter and WaterSense models depend on professional judgement to determine general water requirements of each irrigation zone in a landscape, and use corresponding coefficients and irrigation type and efficiency to calculate water requirement by area. Results from the Hunter model include irrigation scheduling recommendations based on local environmental conditions and water use requirements of each landscape zone. WaterSense and SLIDE quantify recommended water use, but do not include detailed scheduling.

Results of this analysis suggests the degree of complexity in irrigation scheduling models has no significant effect on results. Each model we reviewed approached the determination of landscape water requirements in a unique way, but resulted in nearly identical recommendations. Although each model addresses the basic premise of increasing irrigation efficiency and matching water use with plant type, and each organization developing the models attempts to further refine existing approaches, our review indicates consistent results with no significant difference between methods.

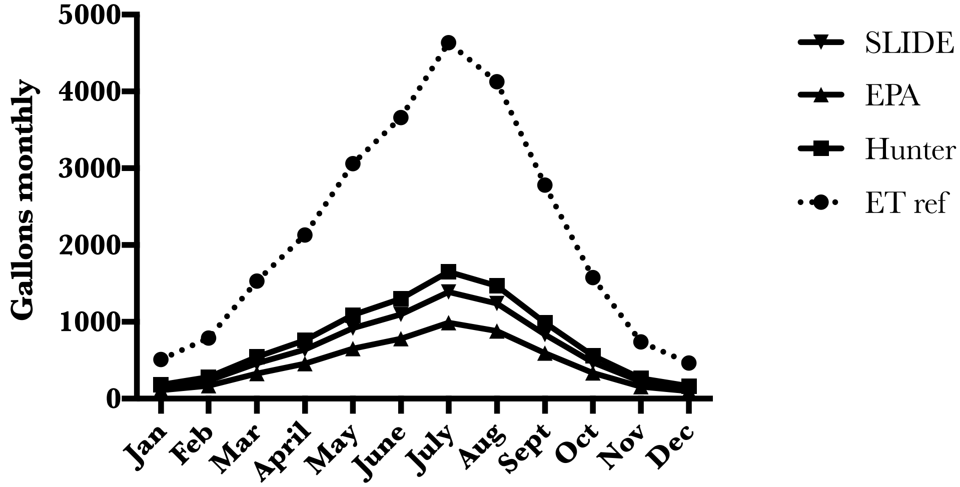

Figure A1.1: Recommended irrigation volume by month following the Irrigation Association's seasonal irrigation timing adjustment (Water Index). Reference ET for Desert Rain is 7.44 inches and is shown as 100% of irrigation volume for July. Figures are gallons per month per 1000 Ft^2. The seasonal adjustment is an averaged percentage of ET reflecting monthly changes in temperature, humidity, and precipitation. The dotted line indicates the historic mean ET rate for Bend Oregon, USA. Results from all models were highly correlated (rs=1.0).

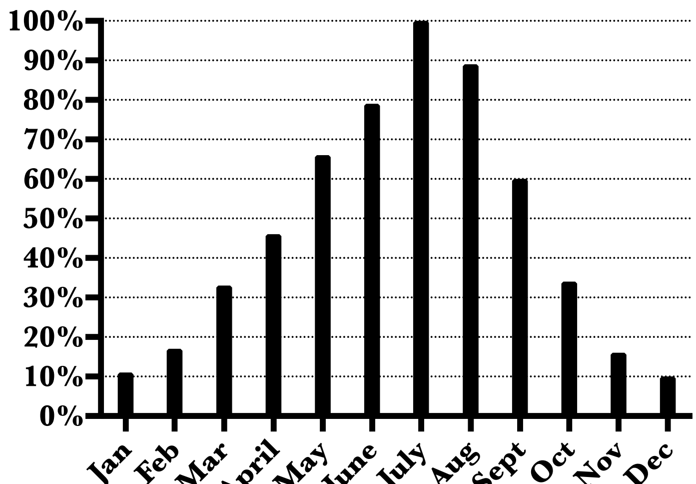

Figure A1.2: Monthly irrigation adjustment percentages used to determine landscape water demand by month at Desert Rain. The percentages are recommendations standardized for semi-arid environments in the western U.S. by the Irrigation Association, and widely accepted as Best Management Practices in the irrigation industry. The peak value (July) represents 100% historical mean ET rate. Irrigation scheduling for each month is determined by multiplying the 100% value by recommended percentages and adjusting timing and rate of irrigation to reflect expected reductions in plant water use in response to decreased rates of evapotranspiration.

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