FEASIBILITY OF RAINWATER HARVESTING FOR URBAN WATER MANAGEMENT IN SALT LAKE CITY

by

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I have read the thesis of Mark A. Jensen in its final form and have found that (1) its format, citations, and bibliographic style are consistent and acceptable; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the supervisory committee and is ready for submission to The Graduate School.

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ABSTRACT

Water managers in the western United States are being challenged by rapid urban growth and limited water availability. The development of new water resources is financially and ecologically expensive shortage management option. Water conservation, recycle and reuse, and increased urban water system efficiency are emerging as less costly alternatives. One alternative gaining national interest for urban water management is rainwater harvesting. Capture and reuse of rainwater near where it falls is an ancient concept practiced in many parts of the world, but it has been relatively ignored in new development in the U.S. Consequently, there is no standardized feasibility and design guidance and no standard specifications at the national level. Further, climate/development variability limits guidance available in other locations from being applied in the mountain west region of the U.S. This thesis takes the first step to address this need by presenting a feasibility study (legal, technical, and financial) of this technology for application in a semiarid mountain west metropolitan area. Using the Salt Lake City metropolitan area as a case study, the thesis explores the legal ramifications of rainwater harvesting under western water law, assesses the technical feasibility of precipitation-water use timing and capture system performance, and presents a simplified cost analysis for residential applications. A daily water balance analysis of single-family residences and a case study residential neighborhood indicates precipitation runoff from rooftops and connected impervious surfaces, respectively, on average can provide

approximately 2-10% of current total residential water use. This percentage remains nearly constant if landscapes are changed to low-water use and increases to 15% for single family homes and 26% for a neighborhood if outdoor water use is eliminated and reasonable indoor conservation measures are implemented (20% reduction in indoor water use). The cost analysis shows that on a neighborhood scale savings in water use will pay for rainwater harvesting in less than a year, and nearly 30 years for a single family residential home. Collectively, the analysis supports the use of rainwater harvesting in municipal water shortage management plans.

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CHAPTER 1

INTRODUCTION

In general, water managers in western United States (U.S.) cities are faced with the challenge of limited water resources and rapid population growth. Typical shortage management strategies incorporate a range of diverse alternatives to meet short- and long-term demands. Las Vegas, for example, faces rapid growth (population has doubled since 1990 to 1.5 million in 2006) and water scarcity (receives an average annual precipitation of 4.1 inches). However, unlike several other growing western U.S. cities (e.g., Phoenix, San Diego), its water managers cannot rely on Colorado River water for its future sustainability because the Nevada allocation is relatively small (0.3 million acre-ft compared to 2.5 and 4.6 million acre-ft for Arizona and California, respectively). Therefore, the Southern Nevada Water Authority (SNWA), the agency responsible for Las Vegas water management, has identified a combination of new water development projects (e.g., controversial Snake Valley pumping and pipeline project (Hutchinson, 2007)) and aggressive water conservation (e.g., paying residents $1 per square foot to remove turf grass (www.lvvwd.com/html/ws_landscape_tips.html)). The situation in other western U.S. cities (e.g., Denver (Denver Post 2007)) is similar with water managers seeking optimal combinations of short- and long-term shortage management options ranging from large water development projects to local conservation efforts.

Salt Lake City (SLC) is representative of the situation in most western U.S. cities.

Growth is rapid (84% population increased projected by 2050) and precipitation is fairly low (16 in/year). Based on population growth an additional water demand of 175 million gallons per day (MGD) is anticipated in 2050 to support urban populations. Water managers serving the SLC metropolitan area are considering expensive and potentially ecologically damaging water development projects, e.g., the Bear River pipeline project has been proposed as means to transport approximately 110,000 ac-ft to SLC and adjacent metropolitan areas (Utah Division of Water Resources, 2000) to meet this new demand. In addition, conservation efforts (i.e., the last oasis (Postel, 1992)) have emerged and new alternatives for managing urban water more efficiently are being investigated (e.g., wastewater recycling and reuse). Actions taken to promote conservation include the creation of a water conservation master plan (Salt Lake City, 2004), promoting conservation through public education campaigns (www.slowtheflow.org and www.conservewater.utah.gov), encouraging water-wise landscaping by amending landscape ordinances in July 2007, creating tiered water rate structures, and identifying and repairing leaks (SLCDPU, 2004).

Although excellent progress has been made in reducing urban indoor and outdoor water use, water managers in the SLC metropolitan area continue to seek additional shortage management opportunities. One opportunity that is gaining national attention (The American Society of Civil Engineers (ASCE) has established a standing technical committee to investigate the technology and offer recommendations for research and implementation directions), but is not currently practiced on a widespread scale in SLC is rainwater harvesting (RWH). RWH in urban areas is accomplished by diverting precipitation to a location where it can be used or stored for later use. The four basic elements of RWH systems are collection area, conveyance, storage, and end use. In its simplest form, RWH is designed to direct runoff from a collection area (e.g., rooftop) to a landscaped area where water is ponded and seepage into the ground is encouraged to support tree and plant growth. RWH in this manner follows low-impact development and water sensitive urban design principles. More complex RWH systems incorporate screening, conveyance, storage, pumping, treatment, and bypass technologies to serve a range of end uses from irrigation to drinking. The rooftop is the common collection area for RWH systems, with other impervious surfaces (e.g., driveways, roadways) also being used.

RWH in SLC is especially intriguing because the precipitation magnitude (including snowfall) is greater than other southwestern states that have begun to adopt the practice (e.g., Phoenix, Albuquerque, and Tucson). However, the climate (e.g., timing of precipitation, snowfall/rainfall mix) and water use patterns are much different, presenting unique technical challenges that have not been adequately assessed. Moreover, the basic legal and economic impediments have also not been considered in the context of SLC. The goal of this thesis research therefore is to conduct an assessment of legal, technical, and economic barriers to implementing RWH in the SLC metropolitan area and other cities in the western U.S. The broader application of the work is the quantification of the impact of landscape conversion from turf grass to low-water use in residential settings on the technical feasibility of RWH in semiarid metropolitan areas.

The research was organized into five tasks: (1) precipitation and water use data collection and quality assurance/quality control, (2) review of legal ramifications, (3) analysis of precipitation and water use data on an annual and monthly basis, (4) development of a daily water balance model to determine required storage tank size and the percent of water use that can be captured, and (5) technical feasibility and cost analysis of residential RWH systems and the impact of landscape modification on future feasibility. The next chapter provides a summary of research and practice as described in the literature. Chapter 3 introduces the analysis methods and model characteristics. Chapter 4 presents the data analysis, modeling results, and discussion. The thesis ends with a summary and offers some final conclusions and recommendation regarding the feasibility of RWH in SLC.

CHAPTER 2

RAINWATER HARVESTING

2.1 Overview

RWH is playing a small role in water shortage management in many parts of the country. The potential for future widespread implementation of RWH is great. There are numerous reasons to implement RWH including desire to reduce stormwater runoff, desire to avoid extending water distribution systems to rural areas, relative cost compared to developing new water supplies, and quality of rainwater compared to existing water source. Although of interest, as of yet a comprehensive assessment of the state of design practices, technologies, policy, and social implications of RWH has not been performed. This review presents a brief, yet comprehensive, summary of the RWH literature.

2.2 Summary

RWH has been practiced in various forms for more than 4,000 years (Reid 1982). For example, applications have been documented in ruins of ancient cities in the Negev Desert in Palestine. Well-known applications were also implemented in the time of the Roman Empire. Cisterns were commonly used in Rome for example on an individual household level and on a wider scale in larger underground caverns (Istanbul, Turkey has numerous examples). Angkor Wat in Cambodia (A.D. 700) created a citywide collection system by directing rainfall-runoff reservoir during the rainy season, and using the water for agricultural irrigation during the growing season. The limited set of examples presented here suggests the potential for RWH to be implemented successfully at a range of scales with relatively limited technology.

In rural areas in many countries, survival is dependent on obtaining a reliable source of water for domestic use and supplemental irrigation. RWH in many cases provides one of the few viable options for water supply. Qiang (2003) described such a situation in rural China and discussed how the use of RWH may have the potential to mitigate poverty in rural areas of China that are not suitable for major water development projects. In cities, RWH is practiced around the world typically using crude, low tech approaches.

Handia et al. (2003) assessed the feasibility of RWH in Zambia, specifically investigating techniques, quality of harvested rainwater, affordability, and economic and socio-cultural aspects. They used a combination of interviews, site visits, and pilot projects using roof harvesting systems. Mass curve analysis was used to determine the storage size, but 10 m^3 cisterns were constructed due to budget limits. The study of water quality was also limited (a single sampling) and produced mixed results - some of the tanks sampled had quality sufficient for drinking by World Health Organization (WHO) standards, but others failed to meet guidelines for bacteriological quality (although it could be used for drinking after boiling). Similar assessments have been completed in other countries.

Ravikumar et al. (2005) describe the use of a geographic information system (GIS) analysis of rainfall patterns, groundwater well records, geology, geomorphology, and soil type (infiltration capacity) to identify locations for artificial recharge of rainwater to maintain sustainable groundwater resources in Chennai City, India. Further analysis of the tool can also provide recommendations of specific recharge strategies including pits, trenches, wells, and sumps/surface storage. The tool was demonstrated for RWH on the Anna University campus (all rainfall directed to recharge pits located at pour point of each delineated drainage catchment on campus) and for roof water harvesting at the Centre for Water Resources (rainfall conveyed from rooftops of the Centre's buildings to seven sumps). For large-scale application in semiarid locations (like SLC) the use of underground storage of harvested rainfall makes more sense than using above-ground surface impoundments subject to evaporation.

A comprehensive review by Meera and Ahammed (2006) of the water quality of rainwater harvested from rooftop capture systems highlights the water quality areas of concern with use of this source for drinking water. They discussed various factors affecting physico-chemical and microbiological quality as reported by Förster (1996) and discussed the first flush effect (Martinson and Thomas 2005). They summarized several studies from different parts of world and suggested the results as a whole show the quality of rainwater harvested from rooftops does not meet basic drinking water guidelines. Coombes et al. (2000) studied the rainwater quality from roofs, tanks, and hot water systems in a section of an urban neighborhood designed to be water sensitive. The two-year study showed water quality improves from the roof to tank to hot water system because of treatment practices. The authors proposed part of the water quality improvement could be from the formation of biofilms on the storage tank surfaces, settling, and for microbiological the heating in the hot water system. The samples from the tank and the hot water system met the chemical and metal criteria of the Australian Drinking Water Standards (did not meet pH).

The Meera and Ahammed (2006) review of microbiological studies included discussion of the effects of quality of roof materials, duration of dry period leading up to rainfall event, rainfall intensity, and storage time (Lye 1989; Vasudevan et al. 2001; and Ghanayem 2001). Additional studies of rainwater quality in Southeast Asia found microbiological quality to be of concern in Thailand (Nantana 1987; Wanpen 1992), Singapore (Appan 1997), and West Malaysia (Yaziz et al. 1989). Appan (1997) concluded rainwater quality data available to guide RWH implementation in Southeast Asia were grossly inadequate. The presence of pathogenic bacteriological contamination (e.g., salmonella) of rooftop runoff has been found (Wanpen 1987; Fujioka et al. 1991), but there have been limited studies connecting microbiological quality of precipitation and captured precipitation and illness. A study by Koplan et al. (1976) showed a potential link between bacteriological contamination (*Salmonella aechevalata*) and gastrointestinal problems. But more research is needed.

Studies have been performed to understand disinfection needs for captured rainwater. A common approach to address water quality concerns is to divert the first flush. Simple disinfection by boiling or adding chlorine is common (Krishna 1991). UV and the use of sunlight have also been explored for disinfection purposes (Fujioka and Chinn 1987; Wanpen 1992).

The Meera and Ahammed (2006) summary of studies of physico-chemical quality suggested in general harvested rainwater meets drinking water quality guidelines, with the exception of pH (Ghanayem 2001; Simmons et al. 2001; Pushpangadan et al. 2001; Chang et al. 2004). Wide variation in concentrations found in the studies was reported. Heavy metals (especially zinc, copper, lead, and cadmium) were found to be an important area of concern due to their presence in harvested rainwater and their toxicity (Davis et al. 2001; Metre and Mahler 2003), although the need for data from developing countries was noted.

Trace organics were the final contaminant category review by Meera and Ahammed (2006). Several studies noted that pesticides may be found in high concentrations in precipitation leading to contamination of harvested rainfall (Bucheli et al. 1998a, b). Recommendations from the review of Meera and Ahammed (2006) included the need for treatment of harvested rainwater if to be used for drinking and the need for further research on proper design and maintenance strategies to minimize contamination.

In some countries federal or municipal leadership has driven standardization and increased sophistication. India and Brazil, for example, are two countries at the forefront of implementing RWH technology in urban areas. Several state governments in India have introduced legislation that requires implementation of RWH into new building construction (Meera and Ahammed 2006). Numerous cities (including Chennai in India and Rio de Janeiro in Brazil) have also mandated the use of rainwater harvesting in new development. In addition regulation, incentives in the form of rebates and subsidies are being used to promote rainwater harvesting.

Koenig (2003) discussed the purpose of rainwater harvesting – public need or a private pleasure. The paper provided a very general overview of the need for rainwater harvesting (alternative drinking water course in light of rising drinking water and wastewater treatment costs, declining groundwater levels, flood control, treatment systems handling excess wet weather flows) and then gave an overview of the European standard addressing rainwater harvesting – DIN 1989 Rainwater Utilization Systems. The standard addresses a major concern with connecting rainwater to the indoor plumbing – cross connections to potable water system. The German drinking water ordinance passed in 2001 did not restrict the use of rainwater inside a dwelling as process water, except in special circumstances for rental property. One interesting point involved the requirement to provide seepage of rainfall because of combined sewer systems being at capacity – this presents further justification for rainwater harvesting use in major U.S. cities with combined sewer overflow problems. The final conclusion of Koenig (2003) was rainwater harvesting could be both – a public need (stormwater control) and private pleasure (cost savings).

Design techniques range from using annual or monthly water balance studies to sophisticated approaches using probability methods. Panu and Rebneris (1997), for example, presented a methodology to determine the optimal size of rainwater harvesting storage for meeting residential irrigation demands. The method is based on application of a graphical or numerical sequent-peak type analysis. To find the optimal storage size, an algorithm was developed that relates the maximum size of landscape which can be supported by a roof catchment area for various probabilities of rainfall exceedance corresponding to given levels of rainfall reliability. The mathematical approach presented contrasts with most of the monthly water balance approaches presented in various manuals available on the Internet.

A model developed at North Carolina State University provides a technical approach integrated into a user-friendly software. The model (which can be executed on the web) allows for a city within North Carolina to be selected, and some parameters for a home such as the number of people, loads of laundry per week, and how much outdoor use. The model estimates the size of a cistern based on the computed of water demand using an hourly water balance approach (www.bae.ncsu.edu/topic/waterharvesting).

Widespread implementation of RWH in the U.S. would require a paradigm shift in planning, design, management, operation as well as social changes to switch from a centralized water treatment and distribution approach to a distributed approach requiring greater knowledge and interaction by the public. A high level of municipal (and federal) commitment will be needed in the U.S. to facilitate the widespread implementation of RWH technology in U.S. cities. Numerous guidance manuals, web portals, and books on RWH are available. The following represent a sampling of those most relevant for RWH application in the U.S.:

Guidance Manuals:

- *City of Tucson Water Harvesting Guidance Manual* (Phillips 2005)
- *Harvesting Rainwater for Landscape Use* (Waterfall and Bickelmann 2006) www.cals.arizona.edu/pubs/water/az1344.pdf
- *The Texas Manual on Rainwater Harvesting* (Texas Water Development Board 2005)
- *Harvesting, Storing, and Treating Rainwater for Domestic Indoor Use* (Texas Commission on Environmental Quality 2007) rainwaterharvesting.tamu.edu/drinking/gi-366_2021994.pdf?pubid=1979
- *Rainwater Harvesting: Supply from the Sky* (City of Albuquerque 1999).

- *Storm Water as a Resource: How to Harvest and Protect Dryland Treasure* (Morgan and Trevathan 2002) www.nmenv.state.nm.us/swqb/Storm_Water_as_a_Resource.pdf

Books:

- *Killing the Hidden Waters: Slow Destruction of Water Resources in the American Southwest* (Bowden 1977)
- *Keepers of the Spring: Reclaiming Our Water in an Age of Globalization* (Pearce 2004)
- *Rainwater for Drylands, vol. 2: Water Harvesting Earthworks* (Lancaster 2007) www.harvestingrainwater.com
- *Rainwater Catchment Systems for Domestic Supply: Design, Construction, and Implementation* (Gould and Nilssen-Petersen 1999)
- *Water Storage: Tanks, Cisterns, Aquifers and Ponds for Domestic Supply, Fire and Emergency Use, Plus How to Make Ferrocement Water Tanks* (Ludwig 2005)
- *Guidance on the Use of Rainwater Tanks, 2nd Edition.* (EnHealth Council of the National Public Health Partnership, South Australia 2004; ISBN O 642 82443 6)
- *Handbook of Water Use and Conservation* (Vickers 2001) www.waterplowpress.com

Web Sites:

- Water Harvesting at North Carolina State University www.bae.ncsu.edu/topic/waterharvesting

- Rainwater Harvesting

  rainwaterharvesting.tamu.edu/index.html

- Centre for Science and Environment

  www.rainwaterharvesting.org/

- Akash Ganga Chennai Rain Centre

  akash-ganga-rwh.com/RWH/WaterHarvesting.html

Reuse of captured stormwater is commonly used in the U.S. for outdoor landscape irrigation. Recent projects, however, are beginning to implement reuse for indoor water demands. For example, Glist (2005) describes the first project in Oregon that has allowed the reuse of stormwater for flushing toilets. The project was used to achieve sustainability goals of the new Stephen Epler Hall on the Portland State University campus. The project involved the use of underground storage of stormwater using the Rainstore3 product.

The United States (U.S.) is not faced with limited access to safe drinking water as is the case in other countries. For example in Lusaka, Zambia a study found 57% coverage of safe water in 1995 (Handia et al. 2003). And WHO/UNICEF (2000) estimates that 1.1 billion people worldwide do not have access to safe drinking water sources. Thus, the reasons for exploring RWH are different in the U.S. than most other countries, especially less developed countries. Reason in U.S. could range from reducing reliance on treated drinking water for outdoor irrigation, supporting the goal of water neutrality, recharging groundwater, reducing stormwater discharges and pollutant loading, and more. Rainwater harvesting is currently practiced widely throughout the world (Salas, 2007):

- Japan
- Taiwan
- China
- Africa
- Australia
- Barbados
- Haiti
- England
- Belgium
- Indonesia
- Banladesh
- Singapore
- Vietnam
- Cambodia
- Thailand
- Phillipines
- Lao PDR

Much, however, is to be overcome before widespread application emerges in the U.S. Water quality concerns, design guidance, land developer and public education, policy changes and incentives, and social and behavioral changes are all needed. A limited number of published research articles related to rainwater harvesting in the U.S. could be found. Rather a large number of conference papers described international studies and applications and numerous guidance manuals for places in the U.S. (mostly in the southwest) were located and reviewed above to provide a comprehensive, but not exhaustive, overview of the literature published on the topic. The literature search did not uncover guidance for RWH applications in Utah or other mountain west states with the distinct dry/hot and wet/cold seasons of Utah. Thus, the research presented below will provide new information for RWH application in SLC and in general mountain west areas.

CHAPTER 3

METHODS

3.1 Overview

The goal of this thesis is to assess the feasibility of RWH in residential settings for Salt Lake City, Utah in terms of (1) legal constraints, (2) potential for precipitation capture meeting water demand, and (3) cost. The legal assessment considered the ramifications of RWH in the context of western water law based on the doctrine of prior appropriation, with specific reference to Utah interpretations. The technical feasibility analysis focused on the problem of precipitation-water demand timing in semi-arid climates with long dry seasons. The cost analysis is based on construction and materials cost estimates. Additional details of the technical and cost analyses are contained below. Results are presented in Chapter 4.

3.2 Annual and Monthly Data Comparison

A standardized approach to analyze the precipitation-water demand timing or to size RWH storage systems does not exist in the U.S. Methods range from annual and monthly analyses (e.g., City of Albuquerque, 2001) to water balance approaches using daily or smaller time steps (www.bae.ncsu.edu/topic/waterharvesting). The approach for this thesis was to begin with an annual assessment and scale down in time to a daily water balance to elucidate the precipitation-water demand discrepancies at different temporal resolutions. Additionally, the multitemporal analysis was meant to highlight the need for a daily (or finer time increment) water balance approach to analyze and design RWH systems for use in SLC.

To perform the technical analyses, precipitation and water use data for SLC were obtained. The daily precipitation record (1943-2003) from the National Weather Service heated gage at the SLC International Airport was obtained from the National Climatic Data Center (NCDC). The SLC airport is located at the northern end of the SLC metropolitan area, 3 miles west of downtown. Although one gage will not accurately represent the spatial precipitation pattern for the entire SLC metropolitan area, it is adequate to provide the temporal pattern specific to the region and representative of locations with long dry seasons necessary to perform the technical analyses described in this thesis. In addition, precipitation in the SLC region is strongly correlated to topography, and the airport is located at a low point in the valley. Therefore, the location will serve as a conservative (i.e., low) estimate of available precipitation. Monthly water use records from 2000 to 2003 were obtained from the SLC Department of Public Utilities. The water use data were summed to the annual level and then averaged to determine the average annual water use for the entire SLC service area. The residential connections were also extracted and averaged on a monthly basis. Finally individual records were randomly selected to develop rooftop-lot-irrigated area size sample sets for the daily water balance study.

The daily precipitation data were summed to the annual level (by calendar year) and multiplied by the area of the SLC metropolitan area (110 mi^2) to determine the annual precipitation volume. A year-by-year comparison of the precipitation volume and the average annual water use volume (based on average of 2000-2003 records) was performed as a first-order assessment of the amount of water demand that could be supplied by captured precipitation. The comparison considers two precipitation capture levels, 95% and 41%. The 95% capture is a theoretical level assuming nearly all precipitation can be captured and used except for small losses (e.g., surface wetting) amounting to 5%. The 41% represents the amount of precipitation capture theoretically possible from hydraulically connected impervious surfaces (rooftops, roadways) in an average residential area in SLC (i.e., the average directly connected impervious area fraction of residential areas in SLC is approximately 41%). Comparisons of annual precipitation to water use were also performed for a 53.5 ac residential neighborhood of quarter-acre lots and for a single-family house with a 1500 ft^2 rooftop area to represent actual case studies of neighborhood and household rooftop implementation of RWH systems. All comparisons were made for outdoor and total water use amounts to assess feasibility for landscape irrigation and the extreme case of total water use provision. For outdoor water use an irrigation pattern of ½ inch 12 times a month for 5 months (typical SLC growing season duration – May through September) was assumed. This rate is based on the Utah Division of Water Resources recommended irrigation for turf grass in Utah's semi-arid climate. To further investigate the timing of precipitation and water demand seasonal and monthly analyses were performed for the entire SLC area, the 53.5 ac residential neighborhood, and the single-family residence with a 1500 ft^2 rooftop area. This was accomplished by using a straight comparison of precipitation volume and water demand.

3.3 Daily Water Balance Analysis

Ultimately, a daily water balance is the most appropriate temporal scale to use to analyze RWH system performance because it will account for timing of precipitation versus water demand at the correct resolution to accurately determine the performance of a storage container. Therefore, the Rainwater Capture Analysis Program (RainCAP) daily water balance program was developed in Matlab to provide rapid analysis of precipitation and water demand records using a water budget to represent the storage and release processes of a rainwater capture system. Given inputs of rooftop size, irrigated area, depth of irrigation, runoff coefficient, number of irrigation applications per month, start and end months of irrigation, water use file, and a user specified tank size, the program computes the percent of indoor, outdoor, and total water demand that can be supplied by captured precipitation. The program is packaged such that it can be applied to a range of spatial scales from the household to neighborhood scale to analyze individual homeowner catchment systems to neighborhood scale retention pond capture systems.

RainCAP was used to analyze the effect of rooftop-to-irrigated area ratios has on system performance. Further analyses were completed to determine how the single-family house performance would change in response to landscape modification from existing conditions (turf grass) to low water use vegetation. RainCAP was also used to study the 53.5 ac residential neighborhood to determine the impact on RWH feasibility of capturing storm water runoff from streets and other impervious surfaces in addition to rainwater captured from house rooftops. The landscape modification investigation was also repeated for the neighborhood. The following subsections describe the RainCAP program, the details of the analyses performed for the single-family house and neighborhood, and the details of the landscape modification analysis. Finally, an analysis of the case of reducing indoor water use in an attempt to achieve water neutrality is described.

3.3.1 RainCAP Computer Program

RainCAP was coded in Matlab to calculate outdoor water demand, and process with monthly water use and long-term data to determine storage size and amount of outdoor and total water demand that can be met. The foundation of RainCAP is a water balance:

$$\frac{dS}{dt} = I - O \tag{1}$$

where ***S*** is volume contained in storage, ***I*** is the inflow rate to storage, and ***O*** is the outflow rate from storage. The water balance accounts for inflows to and outflows from the storage system to compute the change in storage at a daily time increment. Representing this equation in finite difference form produces:

$$\frac{S_i - S_{i-1}}{\Delta t} = I_i - O_i \tag{2}$$

Solving for S_i provides a means to compute the storage at the end of the current time step based on the storage at the end of the previous time step and the inflow and outflow during the current time step:

$$S_i = S_{i-1} + I_i \Delta t - O_i \Delta t \tag{3}$$

Replacing $I_i\Delta t$ and $O_i\Delta t$ with V_I and V_O, respectively, an equation is formed in terms of volumes (storage, inflow, and outflow):

$$S_i = S_{i-1} + V_I - V_O \tag{4}$$

To solve this equation for storage volume, an initial storage volume must be known and then at each time step the volume of water entering storage and the volume exiting storage must be determined. The inflow volume is based on computing the amount of precipitation that can be captured. The volume of runoff entering storage is computed by:

$$\mathbf{V_R = 0.6233 * P * R_C * A_R} \qquad (5)$$

where V_R is the runoff volume (gal), P is the daily precipitation amount (in), R_C is the runoff coefficient (fraction of precipitation converted to runoff), and A_R is the catchment area (e.g., rooftop area) (ft^2). The catchment (rooftop) runoff coefficient can range depending on the land cover, soil type, and slope. An assumed value of 0.95 was used to represent impervious surfaces (rooftops, roadways, etc.) based on the typically used value in engineering practice. To achieve this level of a runoff coefficient for snowmelt would require installing heat tape or other devices to rapidly melt snow and capture prior to sublimation and losses to wind. The computed runoff volume is checked by RainCAP against the available storage capacity, and only the amount of storage available is permitted to enter with the remainder bypassed (not included in the mass balance).

The volume of outflow is estimated to be the daily water demand. During the cold season (no landscape irrigation from November to March) the total water demand is computed using the average SLC per capita per day water use amount based on the records from 2000-2003. An assumption is made that a house has 3.2 persons per dwelling (the average in the state of Utah). During the warm season (April to October, when landscape irrigation is occurring) the indoor water demand is estimated as explained above and the outdoor demand is estimated by:

$$V_{outdoor} = 27152 * A_V * D * T * I_D \tag{6}$$

where $V_{outdoor}$ is the outdoor water demand (gal), A_V is vegetated area being irrigated (acres), D is the depth of water applied to the vegetated area (in), T is the number of irrigation applications per month (times/month), and I_D is the duration of the irrigation season (months). The outdoor water use is calculated on a monthly basis and divided by the number of days in the month to give a daily value. This uniform distribution does not affect the final results because there are few rain events during the irrigation season. RainCAP limits the computed total water demand to that determined on a per capita basis by producing a daily indoor water use for the months of irrigation.

Similar to Equation 5 used to estimate the runoff volume, Equation 6 is subject to considerable variability from location to location. Although uncertain, the equations are expected to provide reasonable estimates for the objectives of this study (RainCAP was also validated against a spreadsheet model as described later). Moreover the equations are designed to study the impacts of landscape modification on technical feasibility of RWH in SLC. The explicit representation of the irrigation scheduling and vegetated area permits those variables to be modified to represent future conditions and then to use RainCAP to determine modified tank size and performance (percent of water demand provided by captured precipitation).

In summary, the input requirements for the RainCAP program are rooftop area, runoff coefficient, irrigated area, depth of irrigation application, number of irrigation applications per month, beginning and ending months of irrigation season, and total monthly water use record. Optionally the user can enter a tank size to determine performance or the tank size is maximized based on the mass balance for a long-term record of precipitation. The RainCAP graphical user interface (GUI) input form (Fig. 1) facilitates data entry. The RainCAP GUI output form (Fig. 2) reports the percent of total, indoor, and outdoor water use captured by computed maximized tank sizes and a user specified tank size. The annual percents (total water captured divided by total water demand for a given year) are determined for each year in the precipitation record. Those values are plotted and summary average percents are computed and displayed.

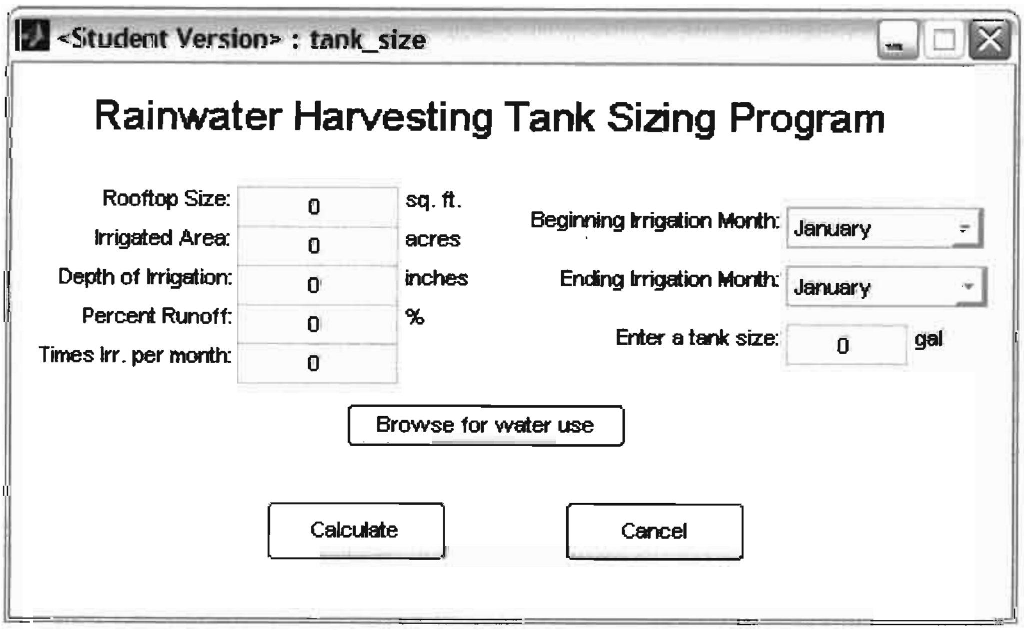

Figure 1. RainCAP input GUI

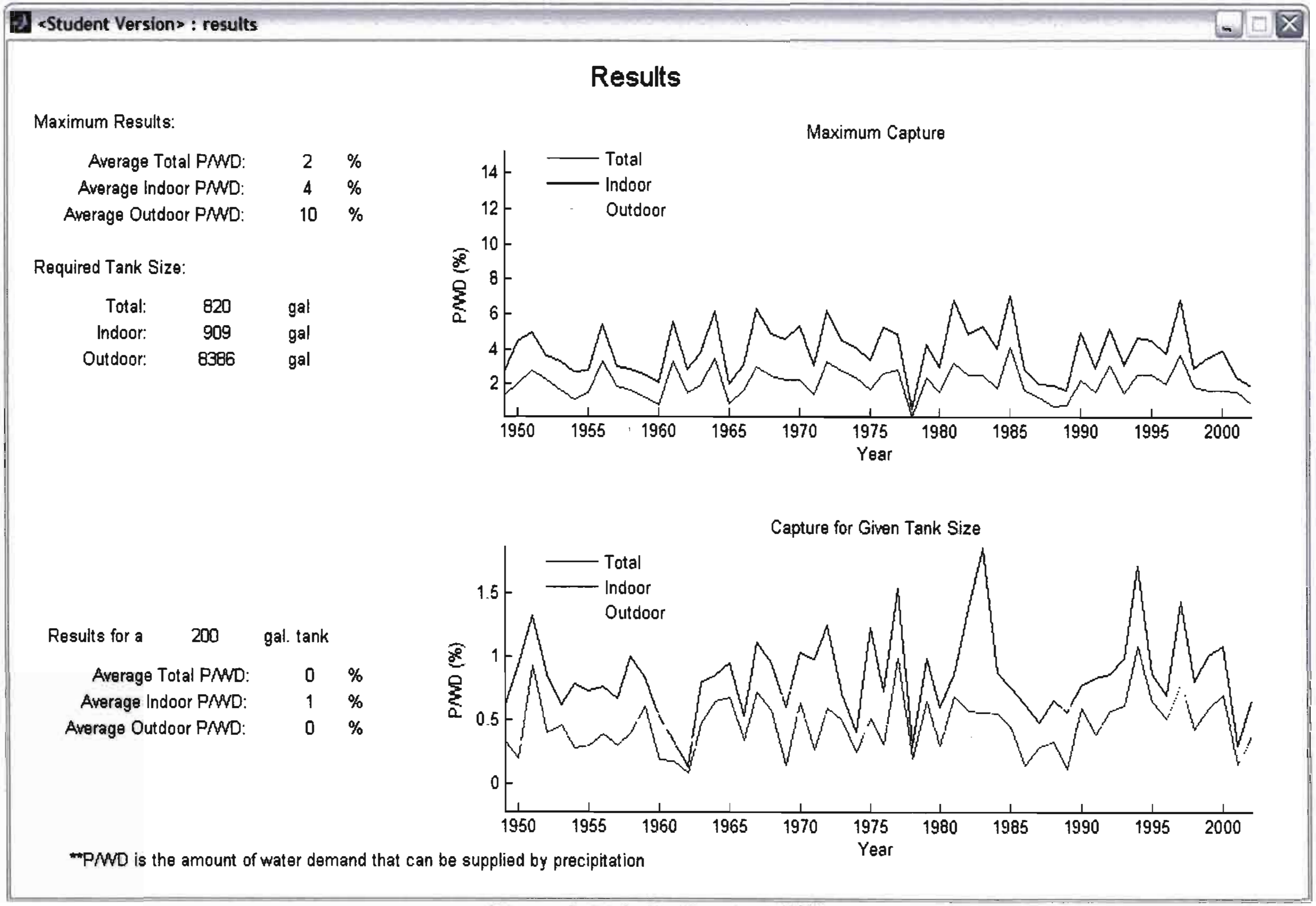

Figure 2. RainCAP output GUI

CHAPTER 4

RESULTS

4.1 Overview

The goal of this thesis is to assess the feasibility of RWH for urban water management in the SLC metropolitan area. Three factors are considered in this feasibility analysis: (1) legal, (2) technical – timing of precipitation and water demand, and (3) cost. Results of the analysis are presented in this chapter. The legal ramifications are first described, providing a brief overview of the constraints of RWH at the household to neighborhood scale. The technical feasibility analysis is described second through a multi-temporal analysis starting with an annual precipitation and water demand data comparison and ending with a daily water balance study of rainwater capture system sizes and performance for a single-family house and a neighborhood. The technical analysis was extended to study the impact of landscape modification from existing turf grass landscapes to low water use landscapes and additionally the impact of indoor water conservation practices on the size and performance of rainwater capture systems. The chapter concludes with a cost analysis of RWH systems at the house and neighborhood scale.

4.2 Legal Implications

Western water law may be the most significant impediment to large scale implementation of RWH. It is based on the notion of "first in time – first in right." This principle is based on a priority date, which is the date that the water right was acquired. In theory the entity owning the right with the earliest priority date will receive their allotment of water regardless of available water. Once they receive their allotment, the entity owning the next eldest priority date receives water and so on. If the water runs dry the most recent priority dated rights go without water (See Utah State Code 73-3-1 and 73-3-21). Another portion of water law in the west is putting the water to beneficial use. This requires that the entity owning water rights must put the water to a designated beneficial use or the right is in jeopardy of being lost. This is also known as "use it, or lose it." The term beneficial use is used in Utah State Code 73-3-1, and proof is required that the water will be put to beneficial use to obtain a water right. If the water is found not being used, the holder of the water right is at risk of losing the water right.

Utah has not yet addressed RWH and water rights in detail because few cases have had to be considered. For most RWH applications the place and time of use remain the same; however, the place of capture changes (from the rooftop by a homeowner or from impervious surfaces in a neighborhood). Through personal communication with Randy a specialist with Utah's Division of Water Rights on October 23, 2007 provided an explanation. If precipitation runoff is captured from "small areas", no change to the water right is needed. The term "small area" was defined by the official as:

- 1 Equivalent Residential Connection (ERC)
- 0.25 irrigated acres
- 10 stock animals

One ERC is essentially a house connection, whereas the other two diversions would be irrelevant in most urban water management circumstances. Therefore, based on this explanation and definition individual homeowners implementing a rooftop rainwater capture system would not need to obtain a modification to the water right. However, implementation at the neighborhood scale would require a request and approval for the water right. To my knowledge, no attempt has been made in Utah to harvest rainwater at the neighborhood or larger scale for urban landscape irrigation or indoor use. There are instances where storm water is captured and detained or retained and allowed to infiltrate (simple RWH system). There are, however, no known cases where runoff is captured at the neighborhood scale and then used for landscape irrigation or indoor use.

In most cities in Utah (including SLC) water rights are leased through a conservation district. This would require the user talk with the respective district to file a point of diversion change. The water previously taken for irrigation water had a point of diversion elsewhere specified by the conservation district. This requires an amendment to the water right held by the conservation district to allow for the point of diversion to be included. Once amended, the water right can then be filed with the State of Utah. It is still unclear, and will remain so until the practice is attempted, how the water management agencies and state would rule on neighborhood scale RWH. At an individual residential dwelling level the Division of Water Rights responses to inquiries suggest RWH would be permitted without a need for water rights considerations.

4.3 Annual and Monthly Data Comparison

The annual analysis was performed to quantify the magnitude of precipitation related to the magnitude of water demand, providing a first-order assessment of RWH feasibility in SLC. The results of the calculation of ratio of precipitation capture to water demand (P/WD) for runoff coefficients of 0.95 (ideal) and 0.41 (residential neighborhood in SLC) are displayed in Figures 3 and 4, respectively. A runoff coefficient of 0.95 (Fig. 3) produced P_{cap}/Water Use ranges of 49% to 136% (average of 88%) and 75% to 210% (average of 136%) of total and outdoor water use, respectively, can be provided by captured precipitation. A more realistic runoff coefficient of 0.41 (Fig. 4) produced ranges of 21% to 59% (average of 38%) and 33% to 91% (average of 59%) for total and outdoor water use, respectively. The plots also display the inter-annual variability of the P/WD ratio. As expected, years with higher precipitation had higher P/WD ratios.

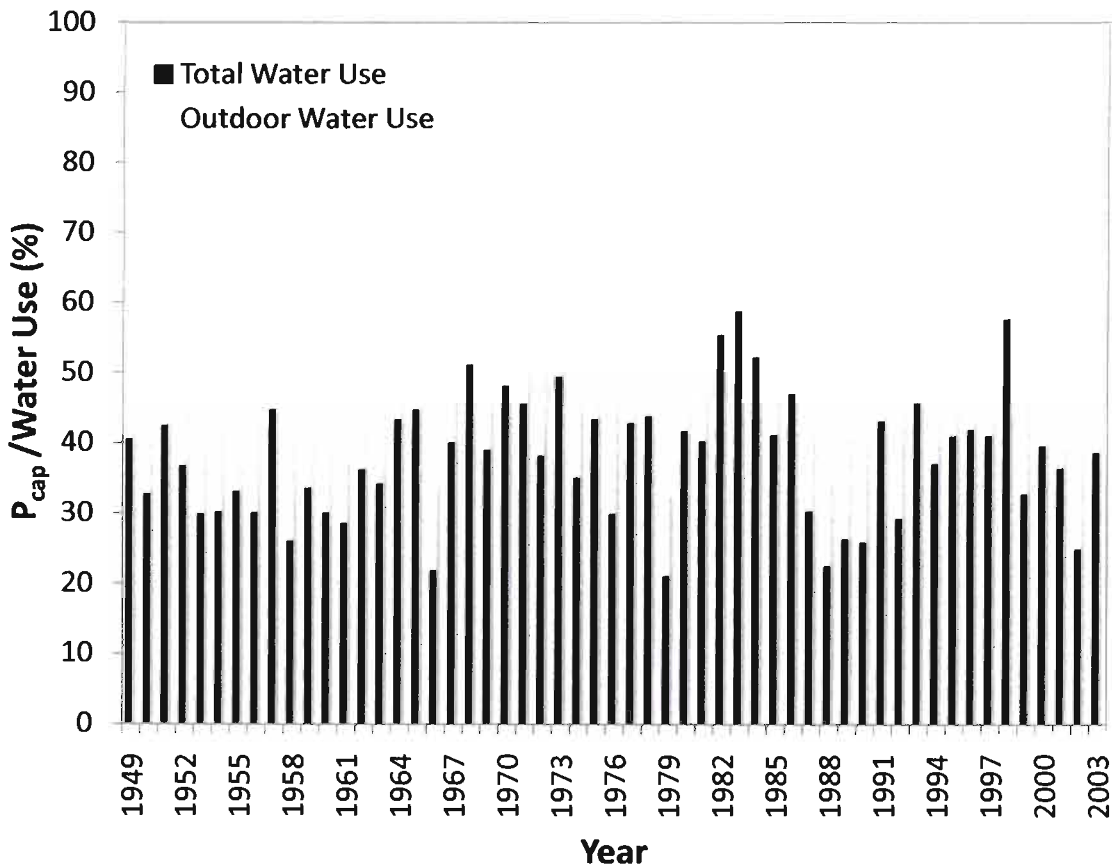

Figure 3. Time series of annual volume of precipitation available for capture (Runoff Coefficient 0.95) divided by annual volume of water use for SLC

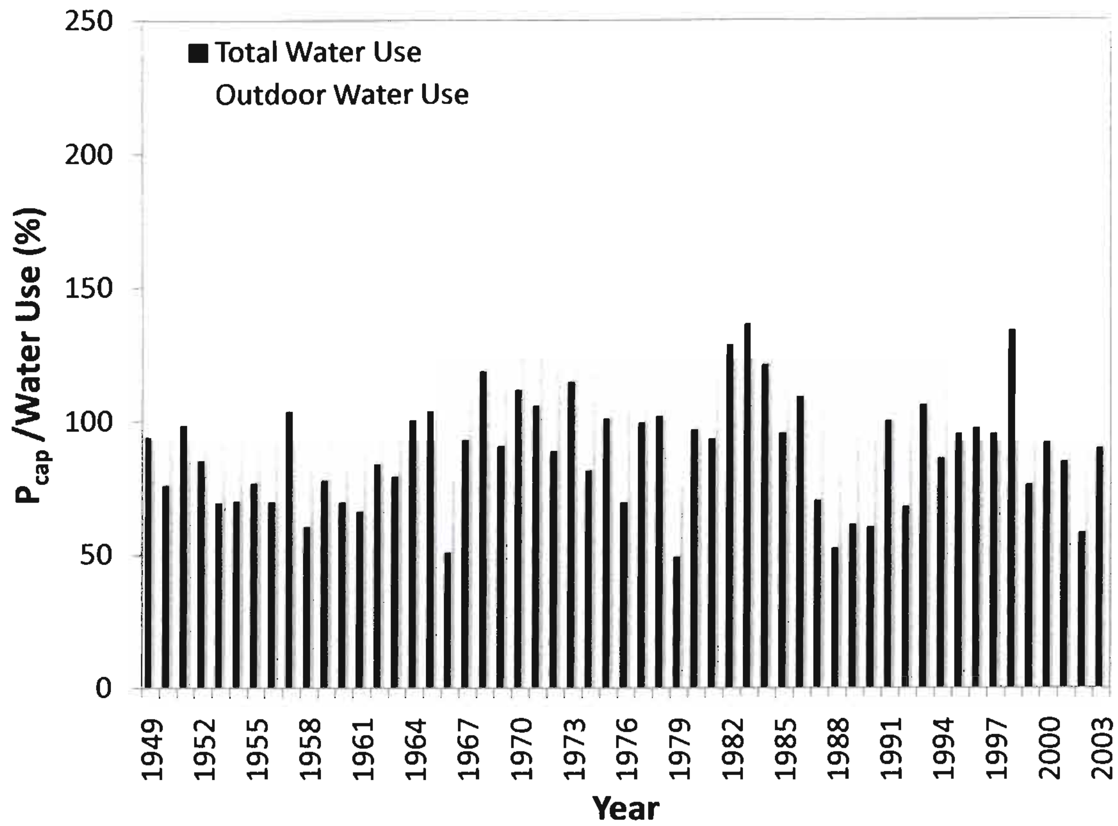

Figure 4. Time series of annual volume of precipitation available for capture (Runoff Coefficient 0.41) divided by annual volume of water use for SLC

The annual analysis was extended by determining at a residential house, the ratio of annual precipitation volume to annual water use and the effect of rooftop size to irrigated area size on the ratio. A runoff coefficient of 0.95 (standard for an impervious rooftop) was used. The total water demand was estimated by assuming a 3.2 person household and 68 gpcd indoor (UDWR, 2001) water demand (both averages for SLC metropolitan area) and the Utah Division of Water Resources recommended values for irrigation of turf grass for outdoor water use. The P/WD (amount of captured roof runoff divided by water demand) ratios were computed for numerous rooftop-to-irrigated area ratios (Table 1). The table indicates a 1000 ft^2 rooftop providing irrigation for 0.04 acres (which corresponds to a 0.1 acre lot) can provide approximately 31% of total water use

Table 1. Annual volume of roof runoff (Runoff Coeffiecent = 0.95) by annual volume of outdoor water demand (expressed as percent)

	Rooftop Size (ft^2)			
Irrigated Area (acres)	500	1000	1500	2000
0.01	61%	123%	185%	246%
0.02	30%	62%	92%	123%
0.04	15%	31%	46%	62%
0.06	10%	21%	31%	41%
0.08	8%	15%	23%	31%
0.20	3%	6%	9%	12%
0.40	2%	3%	5%	6 %
0.60	1%	2%	3%	4%
0.80	1%	2%	2%	3%
1.00	1%	1%	2%	2%

from precipitation capture. This percentage would be providing outdoor and gray water quality (i.e. flushing toilets, washing machine). The construction of an 8,400 gallon underground concrete cistern would cost approximately $30,000 and would take nearly 30 years to save enough (reduced water bill) to pay of the initial costs. Plots of P/WD percent versus rooftop-to-irrigated area ratio (Figures 5 and 6) show rooftop capture can provide 25% or more of outdoor water use for a house with turf grass style landscape if the rooftop to irrigated area ratio is 0.5. As Table 2 shows, the potential for RWH to provide total water use at the household level is less promising. Water use captured by precipitation can provide only a little more than 2% of the total water demand for the average single-family residence in SLC.

Table 2. Annual volume of roof runoff (Runoff Coeffiecent = 0.95) by annual volume of total water demand (expressed as percent)

	Rooftop Size (ft^2)			
Irrigated Area (acres)	500	1000	1500	2000
0.01	4%	8%	12%	16%
0.02	4%	7%	11%	15%
0.04	3%	7%	10%	13%
0.06	3%	6%	9%	12%
0.08	3%	5%	8%	11%
0.20	2%	4%	5%	7%
0.40	1%	2%	3%	5%
0.60	1%	2%	2%	3%
0.80	1%	1%	2%	3%
1.00	1%	1%	2%	2%

A chart can be created from the data presented in Tables 1 and 2. The charts (Figures 5 and 6) provide a simple means to determine the required rooftop to irrigated area ratio to provide the potential to capture a selected percent of water demand using RWH. The water demand values used to determine Figure 5 are based on the Utah Division of Water Resources recommended values for irrigated turf grass. For example, a roof-to-irrigated ratio of 1.0 (rooftop area is equal to irrigated area, which is not out the ordinary for SLC) would be required to capture 60% of outdoor water demand (and 7% of total). The values shown in Figure 6 were based on five actual homes with a similar rooftop to irrigated area and include the assumption that adequate storage can be provided. The actual water demand was used to create the chart. As seen, the values range from 8-19% for P/WD. This suggests that a user's water use pattern significantly affects the results.

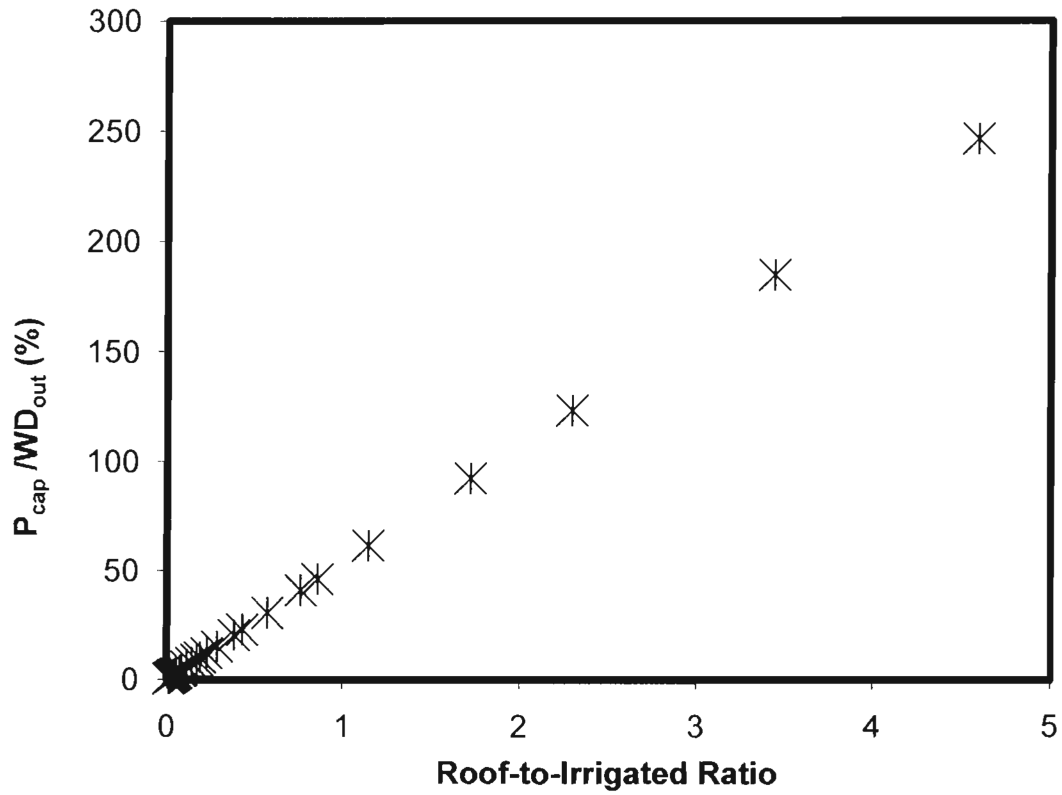

Figure 5. Relationship of annual precipitation volume to outdoor water demand and rooftop-to-irrigated area ratio based on hypothetical water use.

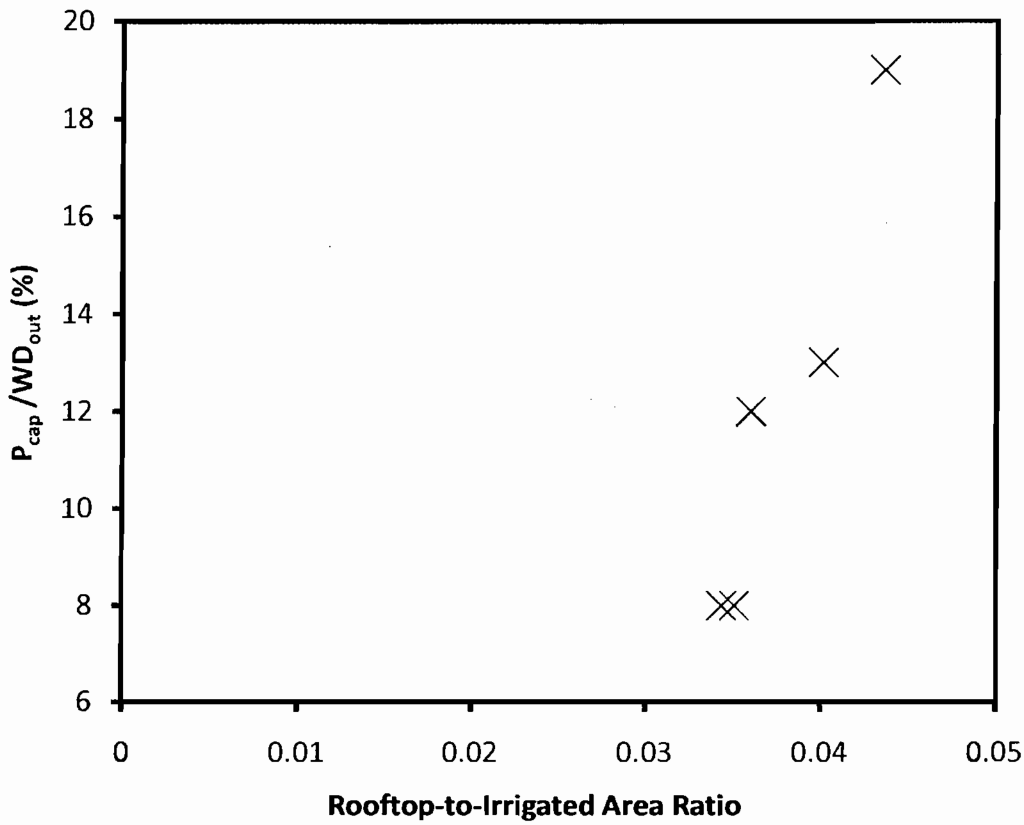

Figure 6. Relationship of annual precipitation volume to outdoor water demand and similar rooftop-to-irrigated area ratio for five homes based on actual water use.

Transitioning to the monthly data analysis, consider Figure 7, which presents a daily comparison of precipitation volume and water use volume for a year (2000 water year) in SLC. The plot shows the results from five independent single family residential homes within SLC. The plot clearly shows the seasonal pattern of precipitation with extremely low precipitation volumes from June to November. From November to April (the wet season) precipitation volume equals 13,500 million gallons (MG) and total (indoor) water use is 8,100 MG. From May to October 11,170 MG of precipitation volume was record to 8,100 MG (21,490 MG) of indoor (total) water demand. The disparity of precipitation timing to water demand suggests the logical need for precipitation runoff capture for later use.

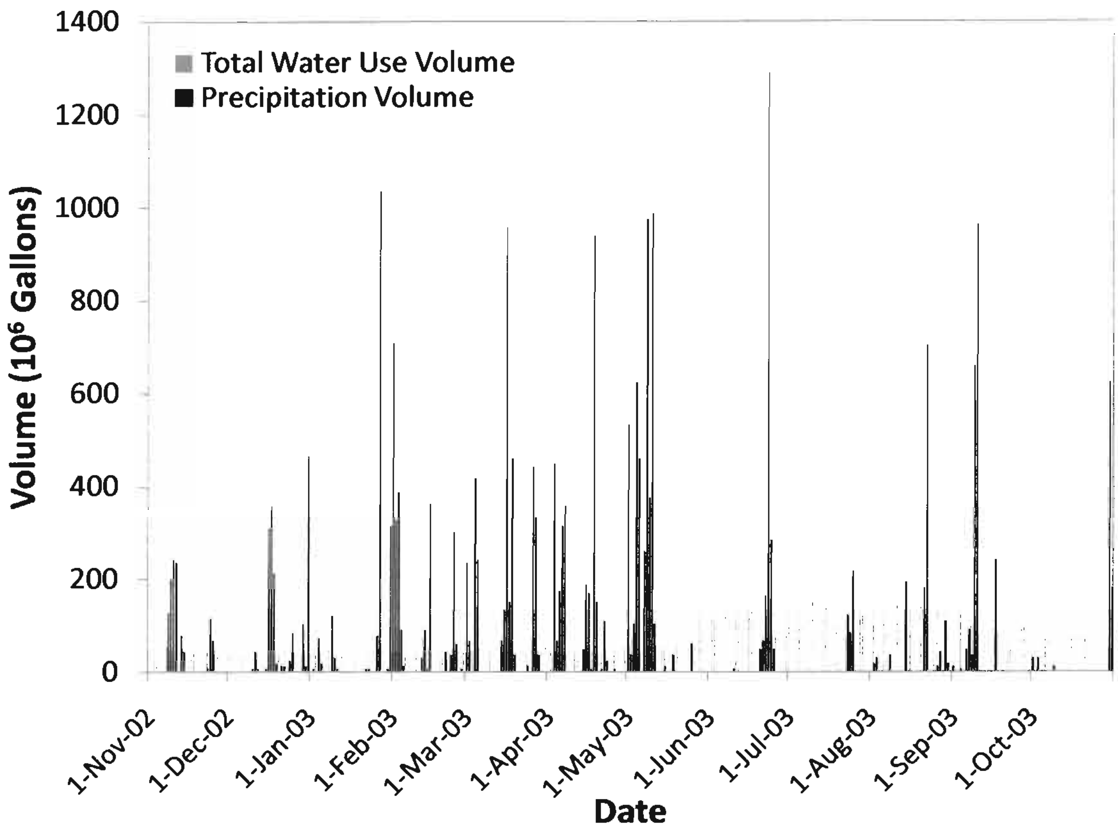

Figure 7. Volumetric relationship of precipitation and total water use for water year 2002

At the monthly time scale, the average precipitation volume in each month based on the 1949-2003 precipitation record was computed. Monthly total water demand was estimated using actual water use data for a residential home. For the neighborhood, monthly water demand was estimated by multiplying the average monthly water demand for house/lot sizes in the study area by the number of houses. The percent of indoor and total water demand that could be supplied each month from precipitation in the specified month was determined for a single-family house (Fig. 8). The same analysis was performed for the neighborhood (Fig. 9). The results show more clearly the problem of precipitation-water demand timing. In the wet season when water demands are lower (no outdoor irrigation demand) the percent of water demand potentially provided by

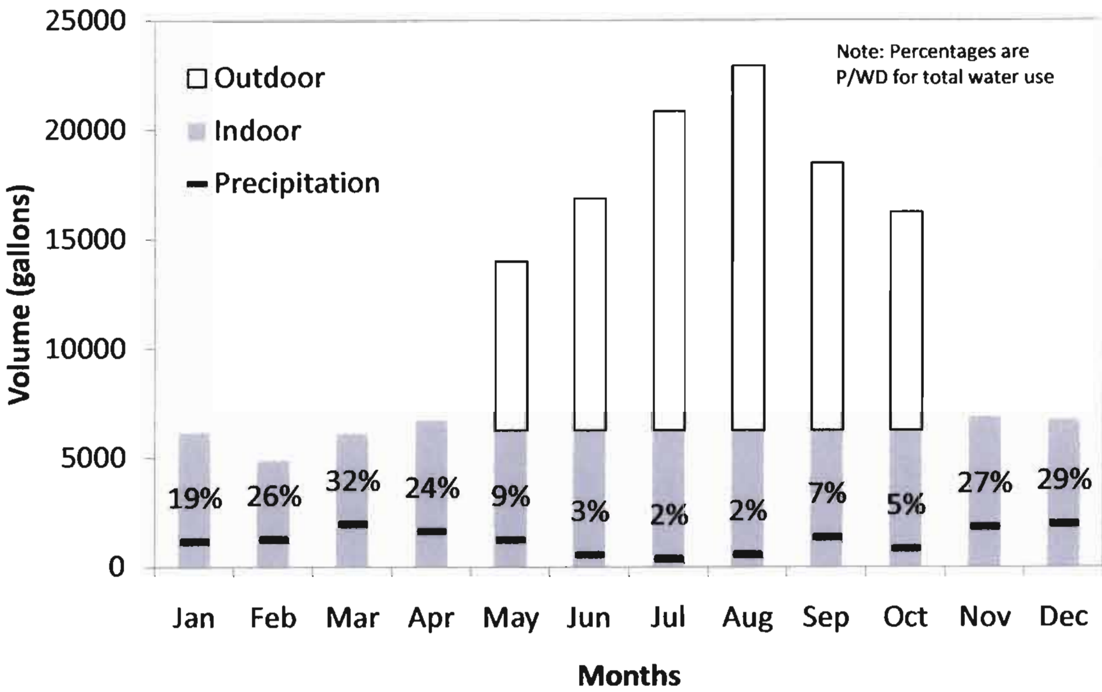

Figure 8. Monthly indoor and outdoor water use for a single family residence in SLC (1497 ft^2 rooftop, 0.05 irrigated acres).

precipitation in that month is 19% to 32% and 34% to 77% for the single-family residence and the neighborhood, respectively. In the dry season (when irrigation is occurring) the percent of water demand potentially provided by precipitation in that month is 2% to 9% and 3% to 20% for the single-family residence and the neighborhood, respectively.

The annual and monthly data analyses show promise for application of RWH to urban water management in SLC. However, the potential of RWH declines as the time resolution decreases. The wet and dry seasons present in SLC are clearly shown in the results and produce unacceptable RWH performance when comparing monthly precipitation volumes and water demand volumes (both total and outdoor) during the dry season.

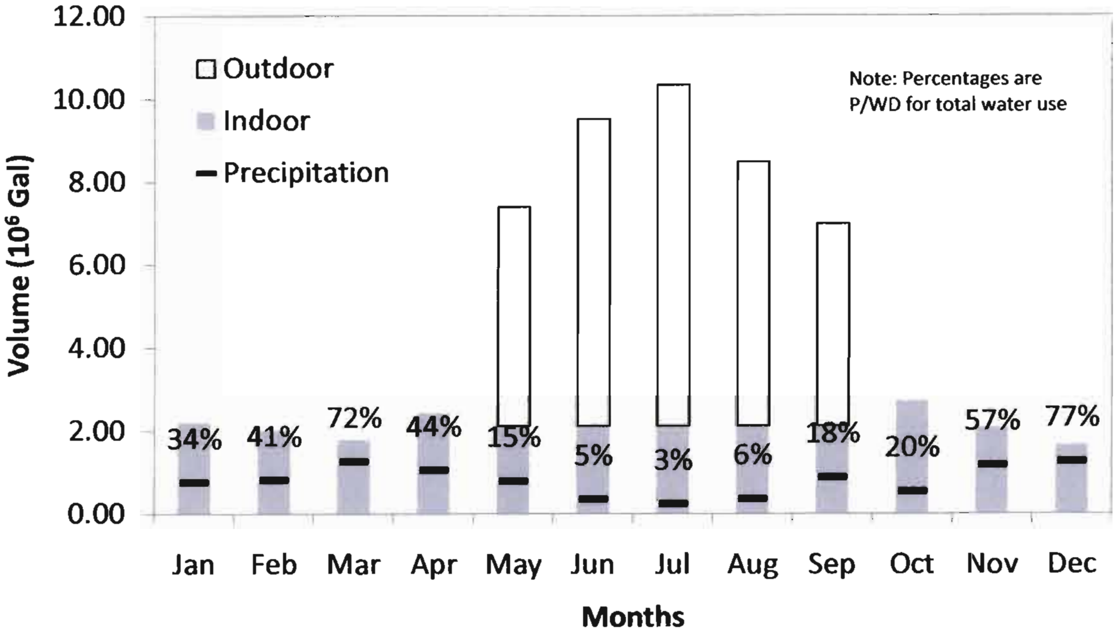

Figure 9. Monthly indoor and outdoor water use for a neighborhood in SLC.

The results are encouraging despite the decrease with time resolution, but clearly the need to continue to decrease the temporal resolution to a daily level to further assess the feasibility of RWH in SLC.

4.4 Daily Water Balance Analysis

The required size of storage tanks cannot be adequately determined using an annual or monthly water balance, but can be with a daily water balance. Moreover, more detailed assessment of the potential for landscape changes indoor water conservation from social/behavioral change or policy implementation can also be studied with more accuracy at a daily time increment.

4.4.1 Single-Family House

The single-family house analysis was performed for small (0.10 acres) and medium (0.25 acres) lot sizes because these are representative of lot sizes for most residential development in SLC. The 0.1 acre lot is found mostly in the downtown area and the quarter-acre lot in the suburbs. Five houses in SLC were selected for a detailed study. The results from RainCAP for the five houses in SLC are shown in Tables 3 and 4. The results differ significantly from those shown in the annual and monthly data comparison for the hypothetical home. The maximum capture (captured precipitation volume divided by the water demand) percents range from 2% to 5% for total water demand to 8% to 19% for outdoor water demand. As expected the house with the larger rooftop area coupled with the smaller irrigated area had the best performance. The required tank sizes to achieve the values shown in Table 3 are moderate for the total water demand (720 to 1869 gal) and large for outdoor water demand (8,359 to 10,666 gal).

The results for the medium lot size (~0.25 acre) produce significantly different results compared with the small lot size (Table 4). Although the roof areas are larger than the amount of outdoor and total water demand that can be supplied by harvested rainwater drops. The percent of outdoor water demand provided by precipitation captured reduces to a range of 7% to 10% because of the decrease of rooftop-to-irrigated area ratio. The tank sizes produced to represent the maximum capture (P/WD) range from approximately 700-11,000 gallons for a 0.1 acre lot and 1,100-18,500 gallons for a 0.25 acre lot. The feasibility of there tank sizes for a single-family home is discussed in the cost analysis section of this chapter.

Table 3. Results from RainCAP showing captured precipitation divided by water demand (total, outdoor) for 5 selected small lot houses in SLC. The tank sizes required to achieve the performance are also displayed.

		1	2	3	4	5
House Size (ft^2):		1497	1529	1750	1568	1900
Irrigated Acres (acres):		0.05	0.05	0.04	0.04	0.03
Maximum Capture (% of use):	*Total:*	2	1	2	3	5
	Outdoor:	8	8	13	12	19
Tank Size Needed (gal):	*Total:*	945	720	942	1,040	1,869
	Outdoor:	8,359	8,539	11,269	10,094	10,666

Table 4. Results from RainCAP showing captured precipitation divided by water demand (total, outdoor) for 5 selected medium lot houses in SLC. The tank sizes required to achieve the performance are also displayed.

		1	2	3	4	5
House Size (ft^2):		2715	2631	2103	2411	2186
Irrigated Acres (acres):		0.07	0.11	0.07	0.16	0.11
Maximum Capture (% of use):	*Total:*	8	4	2	1	2
	Outdoor:	6	9	4	1	2
Tank Size Needed (gal):	*Total:*	8,472	10,228	10,035	1,150	1,466
	Outdoor:	17,463	14,304	9,595	13,525	12,195

4.4.2 Residential Neighborhood

For a residential neighborhood the outdoor P/WD from rooftops only was 5% (1% of total water demand). The total and outdoor water demand produced similar results to the 0.25 acre lot sizes described in the previous section. Adding capture of runoff from directly-connected impervious areas (driveways, roadways) is expected to increase P/WD, the results confirmed this with an increase to 8% for outdoor (11% of total). This is a 3-10% increase in the amount that can be captured. Not only is this more attractive based on the increased volume captured, but the cost are now distributed among 220 people.

4.4.3 Landscape Modification

Selected case study houses were chosen to study the effect of landscape modification (reducing outdoor water demand) on the performance and size of RWH systems. The small lot home selected for this analysis was based on the average house size and water use. Figure 10 shows the result from a house with a 1500 ft^2 rooftop and an irrigated area of 0.05 acres (fairly typical small lot in SLC). The line plots in Figure 10 clearly show the impact of landscape type on RWH feasibility. Changing to low water use landscaping can drastically increase the fraction of outdoor water demand provided by precipitation capture (contributing to achievement of water neutrality). With a moderately sized underground cistern (6,000 to 8,000 gallons) the percent of outdoor water demand that can be provided by captured precipitation increases by six to 12 fold simply by changing from turf grass landscape to low water use landscape. The medium lot and the neighborhood analyses show similar trends (Figs. 11 and 12). The medium lot analysis shows a larger cistern (or two moderately sized cisterns) could be used to capture

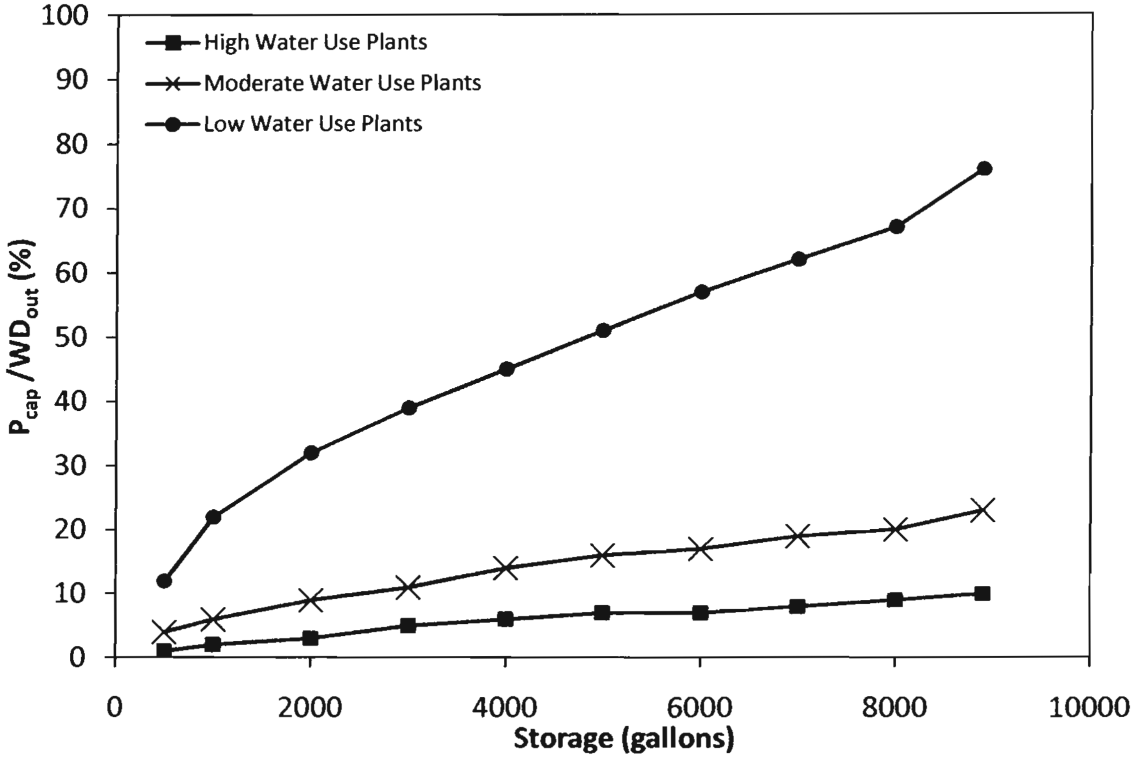

Figure 10. Trends of average annual ratio of captured precipitation runoff volume to outdoor water demand for a small SLC house, lot (1500 ft^2, 0.05 acre irrigated area) as a function of storage tank size.

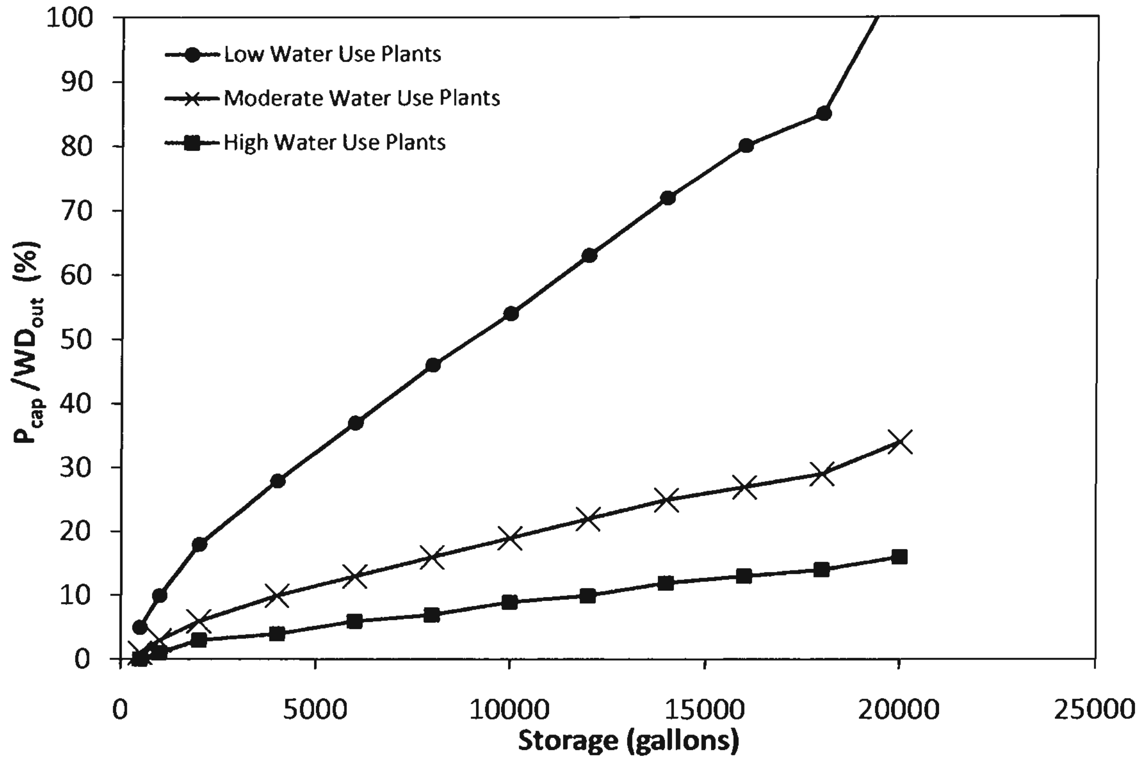

Figure 11. Trends of average annual ratio of captured precipitation runoff volume to outdoor water demand for a medium SLC house, lot (2715 ft^2, 0.07 acre irrigated area) as a function of storage tank size.

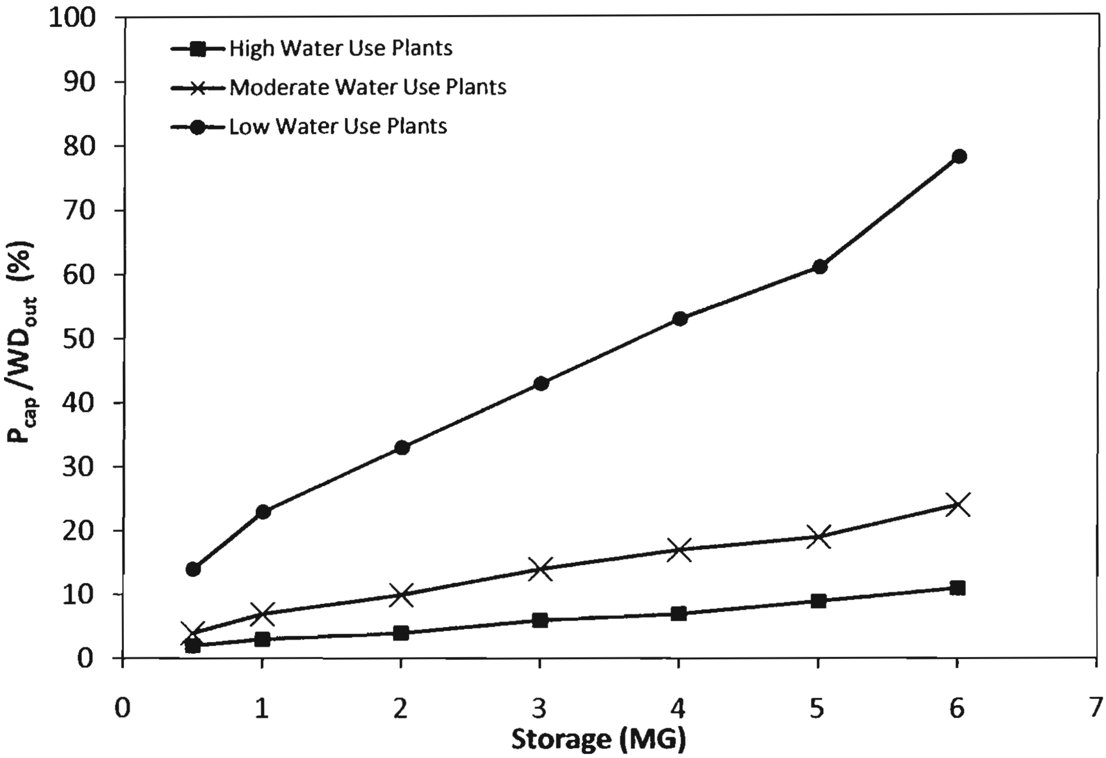

Figure 12. Average Trends of average annual ratio of captured precipitation runoff volume to outdoor water demand for a neighborhood as a function of storage tank size.

100% of the outdoor water demand. And the neighborhood analysis presents a counterintuitive result – capturing water from more areas is expected to provide a greater percent of water demand to be provided by capture, but the results indicate the percent decreases. This could be caused by many variables and is most likely attributed to the actual water values used between the 0.25 acre residential home and the neighborhood. The home size used for the 0.25 acre lot was approximately 1,000 square feet larger than the average home in the neighborhood. This would decrease the amount of precipitation that could be captured in the neighborhood, and increase the amount of irrigated area since the lot sizes are approximately equal.

The same analysis was performed for total water use, however, the graphs were omitted due to the small P/WD values for high, medium, and low water use landscaping. Similar analyses as presented in Sections 4.4.1 to 4.4.3 were also performed for an institutional setting (the University of Utah campus). The results show similar trends and thus are not presented in the main body of the thesis. Rather the results are contained in Appendix A.

4.4.4 Indoor Water Conservation

The final daily water balance analysis is based on the assumption that outdoor water demand is eliminated in a future urban water management scenario (representing xeric landscaping being implemented in SLC that does not require supplemental irrigation). The analysis was performed by incrementally increasing the indoor water conservation magnitude by uniformly decreasing the indoor water demand and running the RainCAP analysis in an attempt to determine the potential for achieving water neutrality (i.e., how much reduction of indoor water use would be revised to achieve water neutrality). Figure 13 summarizes the results of this analysis. The plots of the two single-family residential sizes (small lot and medium lot) and the neighborhood are included in the same figure. Note the lot sizes of houses in the neighborhood are nearly the same size as the medium lot size. The neighborhood can attain water neutrality if indoor water use is reduced 65% below current rates. The medium size lot would require 75% reduction, and the small lot would require approximately 80% reduction. To achieve water neutrality at the household or neighborhood scale would clearly require incredible changes in lifestyle and behavior by reducing indoor water use to 6.8 gpcd which is 10% of current, not to mention converting exterior landscape to xeric.

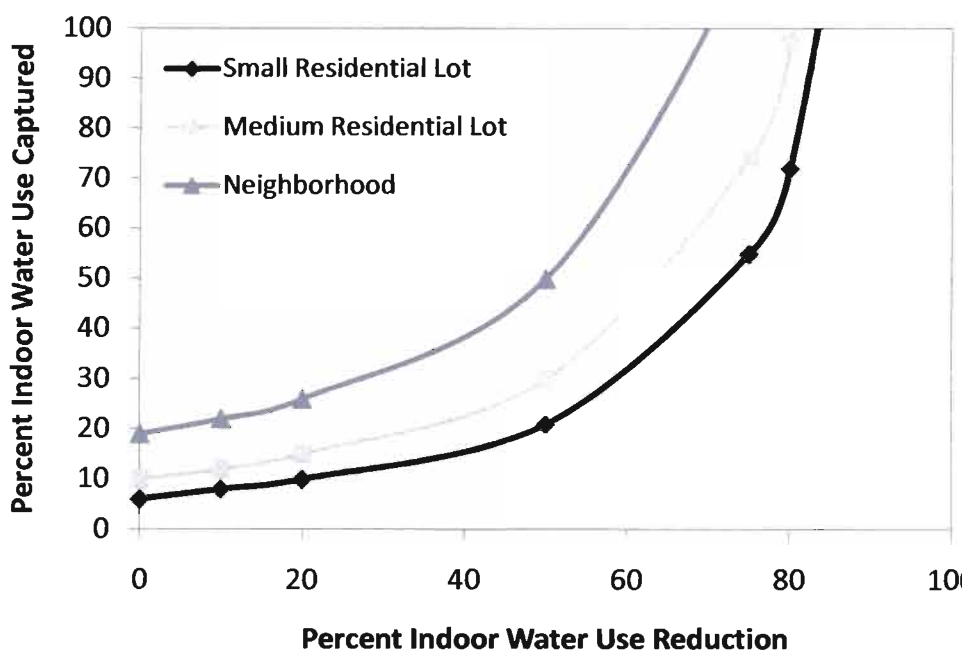

Figure 13. Analysis comparing scenarios based on no outdoor water use and percentage reductions of indoor water use.

4.5 Cost Analysis

The comparison of annual and monthly precipitation and water demand data suggested there was enough precipitation to meet water demands for 41% connected impervious area under any scenario. The daily water balance part of the study suggested the amount of precipitation that could be captured would provide only small amounts of indoor, outdoor, and total water demand. If outdoor landscape changes were made to low water use vegetation and/or indoor conservation measures were implemented the percent of water demand that can be provided by captured precipitation increases. The daily water balance analysis suggests the concept of RWH has potential, but the issue of cost has not yet been analyzed.

The purpose of this section is to estimate costs associated with building a tank or reservoir large enough to meet maximum capture of precipitation given the impervious surfaces available. For determining tank sizes, the dimensions of various tanks are shown in Table 5. These tables show the tank sizes needed to accomplish RWH and are quite large due to the seasonal variations mentioned above.

Table 5. Example tank sizes and their respective dimensions

Tank Size	Dimensions	Material
2000 Gallons	9' X 7.5' X 4'	Concrete
4000 Gallons	12' X 9' X 5'	Concrete
8000 Gallons	20' X 12' X 4.5'	Concrete
2×10^6 Gallons	93' Radius X 10' Depth	Excavated Pond
4×10^6 Gallons	119' Radius X 12' Depth	Excavated Pond
8×10^6 Gallons	150' Radius X 15' Depth	Excavated Pond

Due to the size of reservoirs needed on both the residential home and neighborhood scales the costs have been estimated as will be described in further detail in this section. These costs as well as the time periods needed to pay for the costs are shown below (Tables 6 and 7). The payoff time refers to the savings created from using precipitation capture instead of potable water supplied by the municipality. The amount of water saved is computed by using the P/WD value multiplied by the volume of water demand based on the long-term average. The values shown in the table are computed using the first tier (up to 900 ft^3) water rate for SLC of \$0.82 per cubic foot of water. The assumption was made that the price of water remains constant to remain conservative in the estimate. All costs assumed were construction only and do not contain operation and maintenance. The cost of construction for a residential home includes an underground concrete tank and is approximately \$3.00/gallon. The pump was assumed to be approximately \$5,000 to allow for gray water use. The cost of pumps for drip irrigation systems will start at \$50. The costs associated with a neighborhood include excavation of a reservoir at approximately \$0.50 per cubic foot including a track hoe, dump truck, laborers, and construction management. The pump was assumed to be approximately \$25,000 and basic treatment was \$50,000. However, treatment does not produce potable water quality standards, but for gray water reuse.

The construction costs for a residential home under very progressive conservation methods would take nearly 30 years to payoff the initial construction of the tank. However, costs may be reduced if a polyethylene or other prefabricated tank is used. On the neighborhood scale the savings would take nearly 5 months to pay back. These values do not include needed infrastructure to deliver the water back to the homes.

Table 6. Residential home cost benefit analysis including time needed to pay construction costs

	Tank Size (Gal)	Cost with Pumping	Water Demand (Gal)	Volume Savings (Gal)	Annual Cost Savings	Payoff Time (yrs)
Existing						
Total	950	$ 7,850	37,462	1,498	$ 164	48
Outdoor	8,400	$ 30,200	71,694	7,169	$ 786	38
Low Water Use						
Total	950	$ 7,850	37,462	1,498	$ 164	48
Outdoor	8,900	$ 31,700	16,158	12,280	$1,346	24
20% Conservation						
Total	1,000	$ 8,000	29,970	2,398	$ 263	30

Table 7. Residential neighborhood cost benefit analysis including time needed to pay construction costs

	Tank Size (10^6 Gal)	Cost with Pumping & Treatment	Cost per House	Water Demand (10^6 Gal)	Volume Savings (10^6 Gal)	Annual Cost Savings	Payoff Time (yrs)
Existing							
Total	0.75	$ 124,933	$225	14.8	1.18	$ 129,900	1.0
Outdoor	6.11	$ 483,422	$1,860	21.5	2.37	$ 259,500	1.9
Low Water Use							
Total	0.75	$ 124,933	$230	14.8	1.33	$ 146,100	0.9
Outdoor	6.42	$ 504,144	$1,950	10.3	8.11	$ 889,200	0.6
20% Conservation							
Total	0.95	$ 138,770	$290	11.8	3.08	$ 337,800	0.4

CHAPTER 5

CONCLUSIONS

The goal of this study was to provide a feasibility assessment of RWH systems for the SLC area to assist water managers in their decision making. The feasibility of RWH has been assessed using three measures: (1) legal feasibility, (2) technical/quantitative, and (3) cost. These measures included data compilation, a preliminary comparison of precipitation and water use on an annual and monthly basis, model development, daily mass balance approach, legal research, and a cost benefit analysis. These methods were used to analyze RWH systems in the SLC metropolitan area for current and conservation water demand patterns, and landscaping practices. The legal research and cost benefit analyses help determine overall feasibility for SLC.

The goal of this thesis has been accomplished. The conclusions of the annual data comparison were: A runoff coefficient of 0.41 will provide a P/WD value on average of 0.75 for total and 1.0 outdoor. If developed lots could provide 41% of the area that is available for precipitation capture, 75% of total water use could be achieved.

The larger impervious area available for capture will allow for more precipitation to supply water demand. This is due to the rooftop to irrigation area ratio as seen in the results section of this report. This is accurate for areas with similar water use patterns. As seen in the results section the variation in P/WD was 8-19% for similar rooftop to irrigation area ratios. This was caused by different water use patterns for each of the homes used in the analysis.

Conclusions from the monthly data comparison were:

- The amount of indoor water use that can be captured will be higher in the winter and smaller in the summer because of the seasonal precipitation differences in SLC.
- An 8,500 gallon tank size will be needed in order to capture outdoor water use for a small residential home because of the seasonality of precipitation in SLC. Precipitation falls in greater quantity through the winter when outdoor water use is not being used, resulting in a need for greater storage to capture the precipitation during the winter months.

Conclusions from the daily water balance study were:

- RWH can supply 6-19% of indoor water use.
- Through 20% indoor conservation and native landscaping (i.e. no supplemental irrigation) practices on a neighborhood scale, RWH has potential to provide over 20% of indoor and outdoor use.
- The implementation of RWH through neighborhood conservation will pay for storage tank construction costs in 5 months from municipal water use savings, and the residential home given the same conservation practices will take over 30 years to payoff. From an

economical stand point the neighborhood scale is feasible, and residential homes are not.

Through the development of a RWH guidance manual similar to Albuquerque, Santa Fe, Texas, and Tucson, SLC can begin RWH. This would require further guidance for implementation, education, design methods, endorsement and experienced contractors. The risk-based method (Appendix A) developed in this research can provide the means to design an efficient system in SLC. Through use of common engineering probability analysis (Weibull) a tank can be sized to meet the user's need. Incorporating the risk of economic underutilization (i.e., not capturing enough water to earn back the cost) of the tank into the design can produce more efficient tank sizes.

As water shortage issues continue to emerge in SLC the use of RWH systems on a neighborhood scale can have a short payoff time due to cost savings can help alleviate the problem. The most cost effective way is to create a neighborhood scale storage facility and redistribute the water back to the homes. The economics of additional infrastructure will be required to provide more than the estimate given in this study. The legal aspects will have to be directly addressed, as there is no current policy pertaining to RWH at scales larger that a single family residential unit. The neighborhood scale implemented would require approval from the State Division of Water Rights or conservation district.

This study has emphasized the ability to become water neutral, and some conclusions can be drawn from this thesis. To become water neutral, landscaping would need to be changed to native plants (zero water use plants), and a reduction 65-

80% according to scale of indoor RWH would be needed. The World Health Organization recommended minimum values for survival is approximately 90% of the current indoor water use for SLC. This is not a feasible option because this amount is for minimal hygiene, cooking, and consumption. Water neutrality could be implemented in an emergency, but due to the intensity of change to quality of living it is not feasible for everyday life.

The practice of RWH is feasible and can provide an alternative for water mangers trying to deal with water shortage issues. This study has shown that with cooperative measures on a neighborhood scale make bearing the cost of RWH feasible. The seasonal precipitation patterns require conscientious decisions to be made in design of the proper storage facility. This includes creation of a RWH guidance manual for the SLC, and firm answers to be sought from the State Division of Water Rights on legislative policy regarding RWH. The practice of RWH is feasible and should be implemented to help water manager's provide a portion of water shortage due to growth in SLC.

APPENDIX

RISK BASED APPROACH TO SIZE A RWH TANK

A previous RWH study has performed a risk based analysis for designing rainwater capturing systems. The study was performed for Thunder Bay, Canada. A statistical "Piece-Wise" analysis was performed in order to determine the risk of not capturing enough water to fill the tank. Graphs were shown for the 90% non exceedence probability for precipitation (Panu, 1997). The risk assessment for this Salt Lake feasibility study was based on a Weibull statistical analysis. This analysis included collecting the model output data for each year's percent of water use captured. The Weibull analysis was performed on the actual percent captured value. By determining the Weibull plotting positions and plotting the data, the user can determine the risk associated with any given tank size.

By assessing the risk in designing a tank size for a rainwater collection system will allow for individual feasibility to be addressed. The Weibull plot can be generated for any tank size using the following methods:

- Model output of an MS Excel file called results.
- Results are sorted from smallest to largest and ranked
- Median rank value found for each data point
- Natural log of the natural log of the median rank for each data point is found
- Natural log for each data value found
- Regression analysis using the two different Natural log values using data analysis in MS Excel
- This allows for the alpha and beta to be determined
- Use of weibull function in MS Excel for each data point
- Graph on a log – log axis

These steps are from the www.qualitydigest.com/jan99/html/body_weibull.html website in order to perform the analysis within MS Excel. This analysis was also checked by hand using Weibull plotting positions (see Equation 4) on Weibull plotting paper and was determined accurate.

$$P_i = \frac{i}{n+1} \tag{4}$$

The feasibility of RWH has been assessed and deemed to be a viable option for promotion in the Salt Lake Valley. This leads to a discussion of improving the efficiency of designing RWH systems. Risk is the basis of many, if not all hydrologic designs, in the field of engineering. Therefore, the following results are a means for determining an efficient tank size for the Salt Lake Valley.

This risk assesment has been performed to help determine the user defined failure of the system. With the use of the following plot a comparison could be made between the different scales for current water use, shown in Figure 14. From this figure it can be seen that cluster developments are currently the most efficient possibility for rainwater harvesting. This is based on the fact that the exceedence probabiltiy produces results almost 9% more capture than the next closest alternative, which supports the results of the feasibility analysis.

The next step was taken to analyze the comparison between the scales for low water use. The results for the low water use changes are shown in Figure 15.

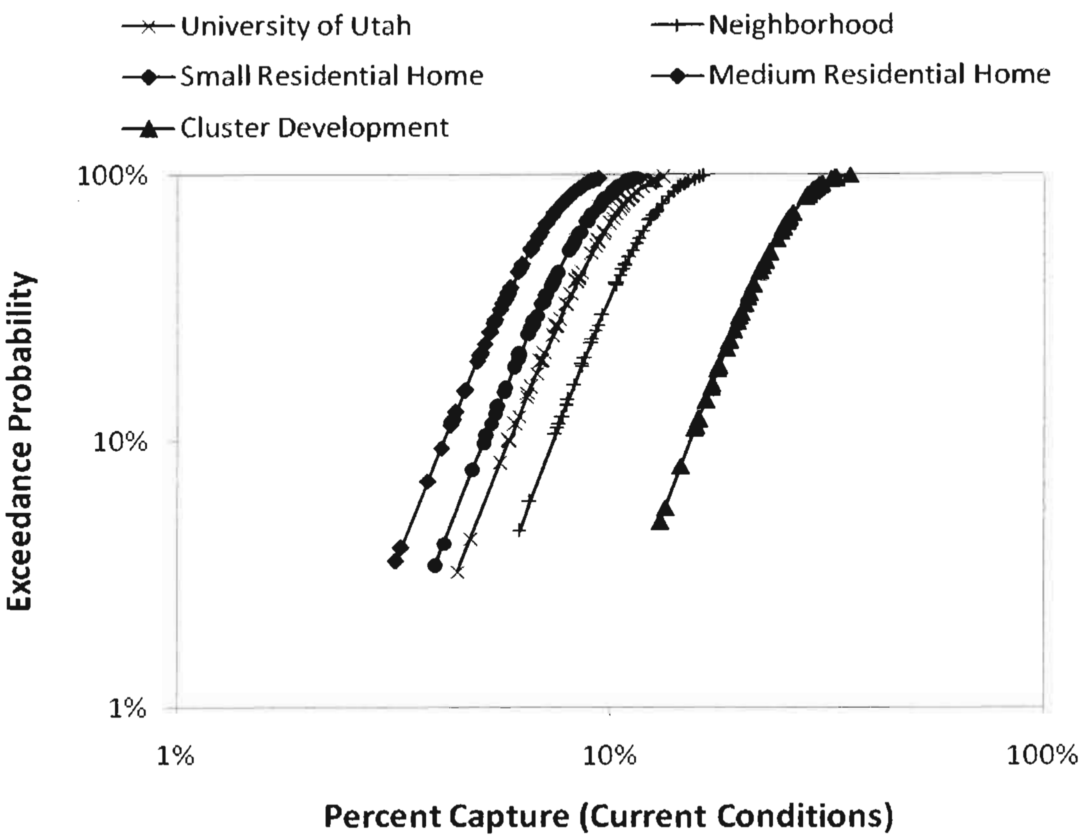

Figure 14. Scale comparison using a Weibull analysis for current outdoor use

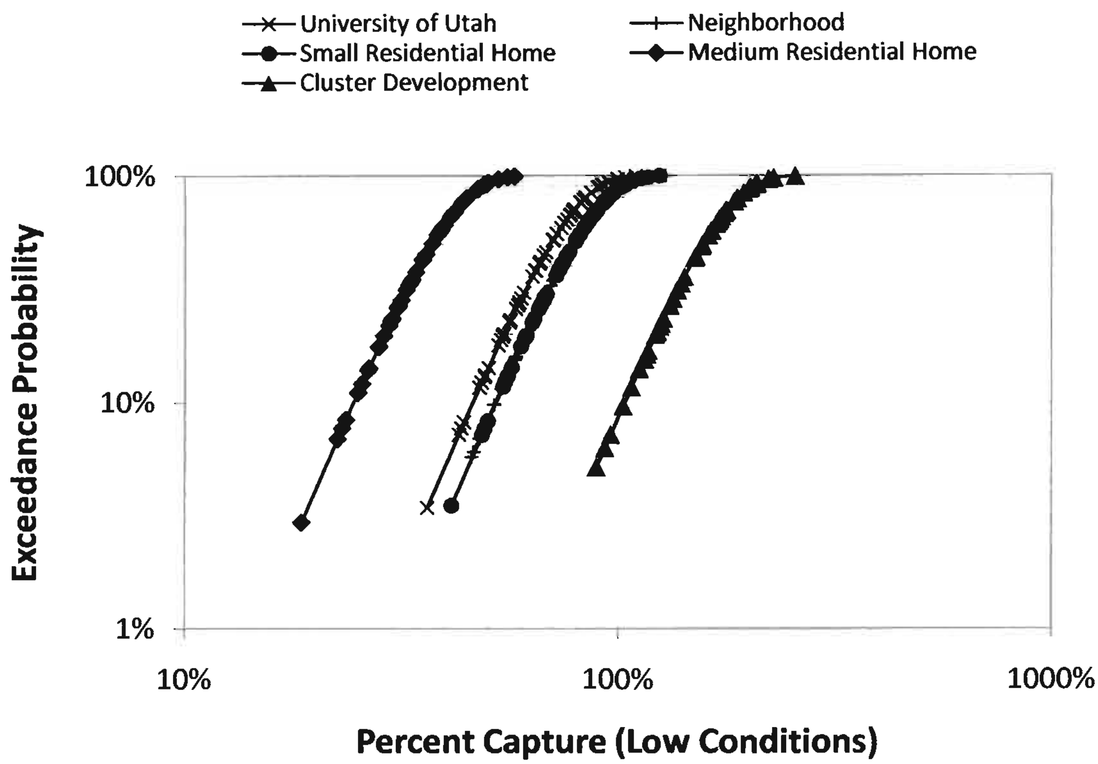

Figure 15. Scale comparison using a Weibull analysis for low outdoor use

From the low water use comparison the cluster homes can capture over 100% with failure about once in 9 years. The smaller homes can capture approximately 21% more than medium sized homes. The neighborhood can capture approximately 5% more than the University of Utah.

This method can be followed to produce an optimized tank size. Consider the following example:

- Single-family residential (0.03 acre irrigated area): Xeriscaped
- Maximum failure probability: 1 in 10 years
- Level of service desired: 30% outdoor water use captured annually

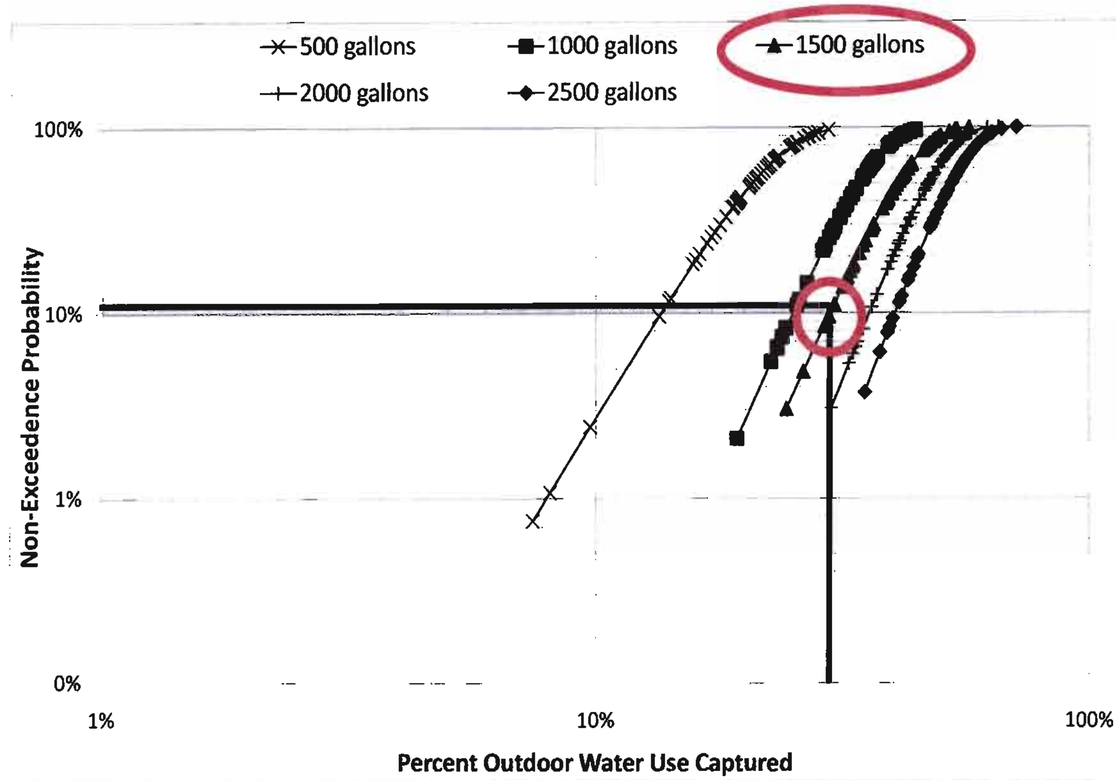

Figure 16. Optimizing tank size using Weibull analysis

- Owner wishes to limit maximum tank size to 2,500 gal based on cost; can the constraints above be met?

As shown (Figure 16) a quick weibull analysis can be performed for various tank sizes to determine if the above criteria could be met to capture a certain percentage of outdoor water use. As shown in Figure 16, the above criteria could be met with a 1500 gallon tank. By still implementing the 2,500 gallon tank, the efficiency of the system will be even greater (approx. 40% outdoor water demand capture).

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