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Adaptation Of Low Impact Design To The Desert Southwest

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ADAPTATION OF LOW IMPACT DESIGN TO THE DESERT SOUTHWEST

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Dedication

Without the bravery of those heroes who sacrificed their lives to defend my hometown (Misurata, Libya) to defend their honour and dignity, and to protect the innocent elderlies, women, and children, and without their stand against a tyranny and a brutal aggression, my parents and all of my extending family would have been war victims and my work would not exist. I cannot express my thanks and gratitude to those martyrs in few words. My work is the least thing that can be dedicated to their pure souls that are fluttering in the paradise. I cannot pass this occasion without mentioning two brave heroes of those; the two young knighthoods who alighted from their horses for us to live in peace. To my beloved cousins Ahmed Mohammad Alamailes (from 1987 to 2011) and Abdurrahman Muftah Alamailes (from 1993 to 2011), I will never ever forget you. Thanks forever.

This thesis is, also, dedicated to my loving parents who always a warm welcome place for me; to my brothers, sisters, friends, and for all whom have prayed for me and have wished me a good luck.

ADAPTATION OF LOW IMPACT DESIGNS TO THE DESERT SOUTHWEST

by

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Abstract

A low Impact Development (LID) practices were used to design an Integrated Management Practices (IMP) system for a residential lot .The design was adapted to the Desert Southwest region based on twenty years of climate data including precipitation and temperature for three representative cities: El Paso, TX, Albuquerque, NM, and Phoenix, AZ. In order to capture stormwater runoff close to its source and to provide as much stored water as possible for plants, LID practices including bioretention cells and vegetated swales were applied throughout the lawn. The purpose of the design is to maintain the pre-development hydrologic characteristics of the site, and therefore not to increase (or decrease) the runoff amount after site development. This will contribute to reduction of the dependence on conventional stormwater management practices downstream. Meanwhile a passive rainwater landscape can be obtained where the water captured by the bioretention units will be stored in the soil and used by native vegetations (shrubs and trees) that will no longer need watering throughout the year once their root establishment period has passed. A water balance was conducted to determine how much green/lawn area can be sustained. The water considered in the balance is that which is available for the plant uptake with a range between the field capacity and wilting point of the soil. Since evapotranspiration is also an important parameter in the water balance, native plants with low water requirements (excellent drought tolerance) and deep-wide root systems were carefully selected for modelling and implementation. Simulation results show that 20% to 50% of crown green/total lot area can be covered depending on the tree to shrub ratio. The change in soil water energy (soil water content and soil suction) was monitored simultaneously in an urban site (residential home) and in a desert at El Paso using, respectively, TDR (Time-Domain Reflectometry) and a soil moisture tensiometer. The collected measurements show that soil at

residential home where some LID practices had been installed can store water for long periods of time.

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1. Introduction

1.1 Introduction

Urbanization affects the water cycle significantly and has been increased by the economic growth and population. In the United States, conversion of rural areas into urban landscapes has exacerbated the problems associated with the stormwater management (Xiao et al., 2007). The conversion of landscapes from pervious to impervious surfaces, such as buildings, roads, and parking lots has changed the ecosystem hydrologic regime significantly (Thom et al., 2001). These changes increase peak and total discharge while reducing infiltration rates. These elements are associated with flooding that threatens people, wildlife, and property. Moreover, surface runoff generated in an urban landscape is more likely to contain a wide variety of pollutants. Furthermore, the groundwater recharge will be reduced, leading to depletion of one of the most important water supplies in the United States. According to a report by American Rivers, the Natural Resources Defense Council, and Smart Growth America (Otto et al., 2002), areas of impervious surface cover can reduce ground water recharge and associated water supplies significantly. The report states that impervious surfaces in Atlanta reduced groundwater infiltration by up to 132 billion gallons each year. This amount is enough to serve the household needs of up to 3.6 million people per year.

This study aims to design an efficient passive landscape using Low-Impact Development (LID) techniques adapted to the circumstances of the desert Southwest. The objective is to contribute to stormwater runoff management, keep the hydrologic response of the watershed like it was prior to development, and to have a greener environment by capturing the rainwater and storing it in the soil, where it can be used by drought tolerant native plants.

1.2 Statement of Problem

The increase in areas of development in the arid desert Southwest in the United States of America has changed the hydrology of the area significantly. The replacement of the surface of permeable desert with impermeable roofs and pavements increases the peak and total stormwater discharge. The generated excessive runoff causes many floods in the region. For instance, on August 1st, 2006, large storms hit the El Paso area and generated flood water, which could not be managed and controlled by the previously installed stormwater management facilities causing failure. The failure of hydraulic structures leads to environmental and property damage. Therefore, in order to manage the stormwater, large and expensive retention and detention ponds are needed, as well as concrete lined channels. In addition, the expansion of the impervious surfaces reduces the water infiltration, and, as a result, the groundwater recharge will be reduced. This will worsen the situation because less water will be available in the soil for the plants, and more municipal water will be used for irrigation. The irrigation water is withdrawn from the groundwater basins, which are not being fed by the stormwater as much as before, so the landscaping will be more expensive. Aesthetically, the view of desertification will emerge because of the disappearance of the green areas, which is replaced by unsightly roofs, pavements, ponds, and channels.

1.3 Objectives and Significances of the Study

The objective of this study is to design an alternative approach to the conventional stormwater management applications. The strategy of the design depends on the Low-impact-Development (LID) approaches and will include the following specifications:

- Small scale system mimics natural hydrologic processes.

- Economically efficient system reduces or eliminates the need for expensive conventional stormwater management facilities.
- Directs runoff to natural areas to encourage growth of native trees and shrubs.
- Enhances infiltration rate into the soil and increase groundwater recharge.
- Preserves the natural drainage patterns.
- Helps to prevent erosion in the watershed by capturing the runoff in small bioretention units and keeping it less likely to reach the damaging flow rate.
- Distributes the water storage volume among the bioretention unites for the system to be more robust thus failure of one component will not cause the entire system to fail.
- Eliminates the need to irrigate landscape by using the water stored in the bioretention units to grow native and high drought tolerant trees and shrubs.

In addition, this study includes an investigation about the behaviour of the water stored in the soil throughout an entire year in order to:

- See the change in the water content and the soil suction
- See the relationship between the water content and the soil suction.
- Compare the water conservation in soil at the low impact development practices and in a natural site in the desert.

1.4 Study Area

The study area includes the arid desert southwest. According to Geographer D. W. Meinig (1971), the core of the Southwest includes the portion of New Mexico west of the Llano Estacado and the portion of Arizona east of the Mohave-Sonoran Desert and south of the "Canyonlands", and also includes the El Paso district of western Texas and the southernmost part

of Colorado. In this study the area is represented by three cities: Phoenix, Arizona, El Paso, Texas, and Albuquerque, New Mexico. These cities were selected for the study because they have high populations and intense development, which make them a likely subject to the stormwater management problems.

According to Köppen climate classification, all of these cities are considered arid, meaning they have a similar desert climate with very hot summers, usually with little or no humidity, and dry warm winters. The elevations of these cities are higher than sea level: Albuquerque has the highest level with 4,900 feet, followed by El Paso with 3,800 feet and then Phoenix with 1,117 feet.

1.5 Low-Impact Development (LID)

Low Impact Development (LID) is a stormwater management approach, which is fundamentally different from conventional methods (USDoD, 2004). It has been adapted for many years in many states across the United States. LID has many practices that can be used to manage stormwater by carrying it in small, cost-effective landscape features located on each lot rather than in large, costly pond facilities located at the downstream of drainage areas. The goal of LID implementation is to mimic the predevelopment site hydrology by using site design techniques that store, infiltrate, evaporate, retain, and detain runoff. The LID implementation can produce an improved environmental performance and generate lowered development costs when compared to conventional stormwater management approaches. Moreover, it can naturally and effectively remove many pollutants such as nutrients, pathogens, and heavy metals from stormwater (US EPA, 2007). LID Cost savings are achieved when the runoff is minimized

through infiltration and evapotranspiration rather than being conveyed by pipes or channels and managed downstream in large scale stormwater management facilities.

The LID practices contribute to formation of Integrated Management Practices (IMP) based on the properties of every site.

1.6 Manuals Survey

Unified Facilities Criteria (UFC), published the Low Impact Development Manual in 2004 before some modifications were added to newer versions in 2005 and 2010. This UFC (13514UFC 3-210-10) is under revision to comply with new legislation and policies; this complies with the Energy and Independence Security Act (EISA) Section 438 and Executive Order is 13514.

This manual provides detailed information about the most common and well-researched integrated management practices (IMP) of LID in terms of appropriate use, typical cost, maintenance needs, and commonly required corrective actions. These practices include the soil amendments, bioretention cells, dry well, filter strips, vegetated buffers, grassed swales, infiltration trenches, inlet devices, rain barrels, tree box filters, vegetated roofs, permeable pavers, and permeable pavements.

For this study two LID practices were selected from the manual. The first is the bioretention cell (Figure 1.1), which is a depression that contains porous backfill under a planted surface. The porous backfill increases the infiltration rate while plants will also facilitate runoff infiltrating and increase the evapotranspiration.

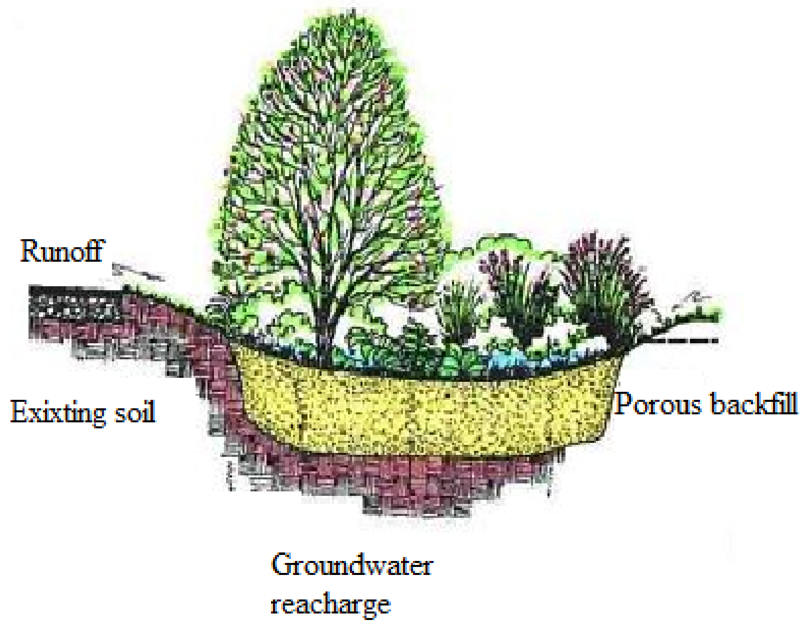

Figure 1.1: Bioretention Cell. (PGDER, 1999)

The second practice is the vegetated swale, which is very much functionally similar to the bioretention cell. The difference is that vegetated swales are narrower than the bioretetion cells; therefore, they are used when there are limited spaces.

The manual gives a clear explanation for LID site planning process. This explanation shows the steps of model planning process, LID control strategies, design LID site, and operation and maintenance procedures.

Additionally, and for more clarification, two LID site design examples were included in this manual. The first example shows how an existing building complex can be retrofit with LID practices. The first step of this design was to determine the objectives including the integration of water quality management practices into the repaving of parking areas, the sidewalk repair, and the area re-landscape. The second was to rank and prioritize project opportunities such as reducing non-point source pollutant loads and minimizing the costs for new structures or materials. After that, the site conditions such as the existing drainage system, the site topography,

and the soil type were investigated for the design requirements. Based on the previous steps, the site was divided to eight drainage areas with four LID practices, including bioretention, permeable pavers, tree box filters, and a vegetated roof, were selected. The purposes of this retrofit design were removal rates of 70% by bioretention and tree box filters, and a removal rate of 50% by permeable pavers. Calculations were performed for lead, copper, zinc, phosphorus, and total nitrogen. The results show an overall reduction of almost 65% of the aggregate load for the areas directly controlled by the practices and 55 % of the total annual load for the pollutants studied.

Table 1.1: The Projected Load Reduction for Various Pollutants. (USDoD, 2004)

Pollutant	Annual Load Existing Condition, lbs	Annual Load After LID Retrofit, lbs	Removal Rates %
Zinc	17.5	6.1	65
Lead	17.1	6	65
Copper	4.6	1.6	65
Nitrogen	95.6	33.2	65
Phosphorus	44.5	15.5	65

The second design example provided in this manual was a comparison between conventional and LID stormwater management designs for a new house in a coastal area. The comparison categories included the peak runoff rate maintenance and the water quality control for 2-year 24-hour storm, and 10-year 24-hour storm.

The results showed that for the 2-year 24-hour storm, the LID site design results in a 46% reduction in required storage volume as compared to the conventional site design, and for the 10-year 24-hour storm, the volume reduction is 38%.

City of Tucson, AZ (Phillips, 2005) published a Water Harvesting Guidance Manual. This manual identified the principles of stormwater runoff harvesting and explained its benefits in reduction of the site discharge, erosion, pollutants transport, the dependence on conventional

stormwater management practices, and accordingly the cost reduction. In addition, the manual provided the water harvesting design process which can be summarized in five steps, including adopt an integrated design process, analyze site characteristics and conditions, identify the potential to use harvested water and other site resources, develop an integrated design for the site, and prepare detailed designs. Moreover, a group of water harvesting techniques are illustrated in detail in this manual. These techniques have the same characteristics of LID where they are used to collect and reduce the runoff at the closest point to the discharge sources. However, they are not mentioned in the LID manual. These practices including microbasins, swales on-contour, swales off-contour, French drains, gabions, water tanks, and mulch are explained in terms of appropriate siting, construction, vegetations, maintenance, and variations.

French drain is one of the practices that are selected to be a component in the integrated management practices of the low impact design in this study. It is a narrow trench filled with rocks or coarse gravel (figure1.2) to encourage a rapid infiltration and to convey the runoff from the source to the target point.

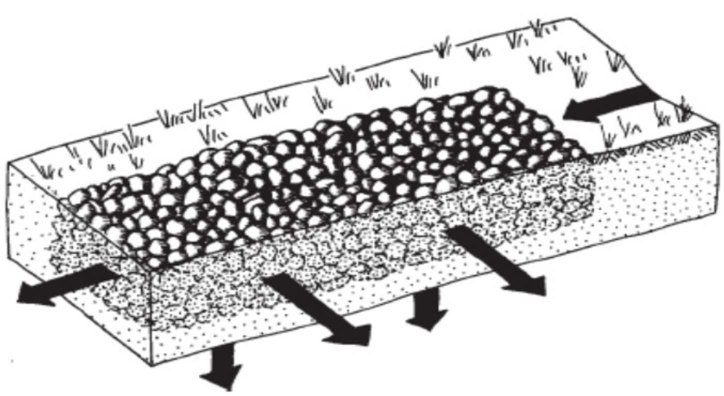

Figure 1.2: French Drain. (Phillips, 2005)

Finally, the manual gave some water harvesting design examples explaining the design procedures for different site use levels including subdivision, commercial site, public building, and public rights-of-way.

Texas Agricultural Extension Service, 2001 published the Xeriscape, Landscape Water Conservation B-1584-5-01. The term of xeriscape refers to landscaping in ways that reduce or eliminate the need for supplemental water from irrigation and it is promoted in regions that do not have easily accessible, plentiful, or reliable supplies of fresh water. In this version the Texas Agricultural Extension Service strongly encourages people to adopt Xeriscape in order to reduce water use in landscape implementing.

Seven principles of water saving are simply explained to be applied together to obtain an optimum Xeriscape landscaping. The first principle is planning and designing the site where it should have efficient water consumption. The second principle is to determine the soil conditions in order to know what is the quality and quantity of fertilizer needed. The next principle is to be practical and familiar with the variation in water need, maintenance, and watering ease between the different kinds of turf areas and vegetations. The fourth step is to select appropriate plants where they should be native to the region of the site. Grass turf is not recommended because of the high water requirements. Attached to this publication are tables of the native and recommended plants for the different regions in Texas which are distinguished to six areas shown in figure (1.3).

Figure 1.3: Texas Plant Adaptation Map. (Douglas F. Welsh, William C. Welch, 2001)

After selecting the plants, an efficient watering program is needed to keep the plants alive and meanwhile apply as little amount of water as possible. An important point should be considered herein about the plants' roots, where the newly planted shrubs and trees should be frequently watered until their roots are established. When the root establishment is completed, water should be applied less frequently to make the roots go deeper into the soil. Next, an efficient water irrigation system should be selected to give the plants their water requirements without wasting the water. The next step is to cover the area around the plants with mulches, which could be organic materials such as pine bark, compost and woodchips, or inorganic materials such as lava rock and limestone. The purpose of mulch application is to reduce the evaporation from the soil surface and keep it moist for a longer period. The last principle is to have a good maintenance strategy allowing occupants to keep the landscape performing well for a long time.

1.7 Literature Survey

Seckin, Y. C. (2010) discussed a study conducted in Umraniye, Istanbul, comparing a conventional residential irrigation system and an alternative system containing two water sources: graywater (household wastewater excluding toilet water) and harvested rainwater. The irrigation systems were designed for a specific site (residence) to evaluate their performance. For the rainwater harvesting system, the available water was calculated based on the square footage of the house footprint and the amount of average annual precipitation. A collection efficiency of 85% was selected to estimate the rainwater lost to fresh flush, evaporation, and leaks from the joints.

AMR= Catchment area × Seasonal rainfall × collection efficiency

Where AMR = Amount of harvested rainwater. (1.1)

The irrigation water demand was estimated by calculating the number of irrigation days and the water demand of the plants, which were 6-7 mm/day for lawn grasses and 4-5 mm/day for shrubs and trees based on Melby, 1995. The following steps were applied to obtain the water demand in liters:

NID (day) = Total no. of days in dry season – No. of rainy day in dry season

Where NID = Number of irrigation days. (1.2)

TWD (liter) = [(lawn grasses area × water demand) + (shrubs & trees crown area × water demand)] (liter/day) × NID(day). (1.3)

Where TDW = Total water demand.

A LID rainwater catchment system was designed for this particular case. This system, as it can be shown in figure (1.4), has many components. Economically, this study concluded that saved money would barely be enough to change wasted parts in the system. However, this study explained that although there are economic difficulties and availability problems, alternative water systems are not considered potable water supplies, which is important for the future of civilization. Water reuse and conservation at the household level will also help to reduce stormwater runoff into municipal storm sewer systems. At the same time, it recharges the groundwater, which is one of the most essential potable water supplies. In sum, this study found that municipal water is still an economically sufficient source for residential system in Istanbul. However, in terms of sustainability, graywater and harvested rainwater are the preferred sources.

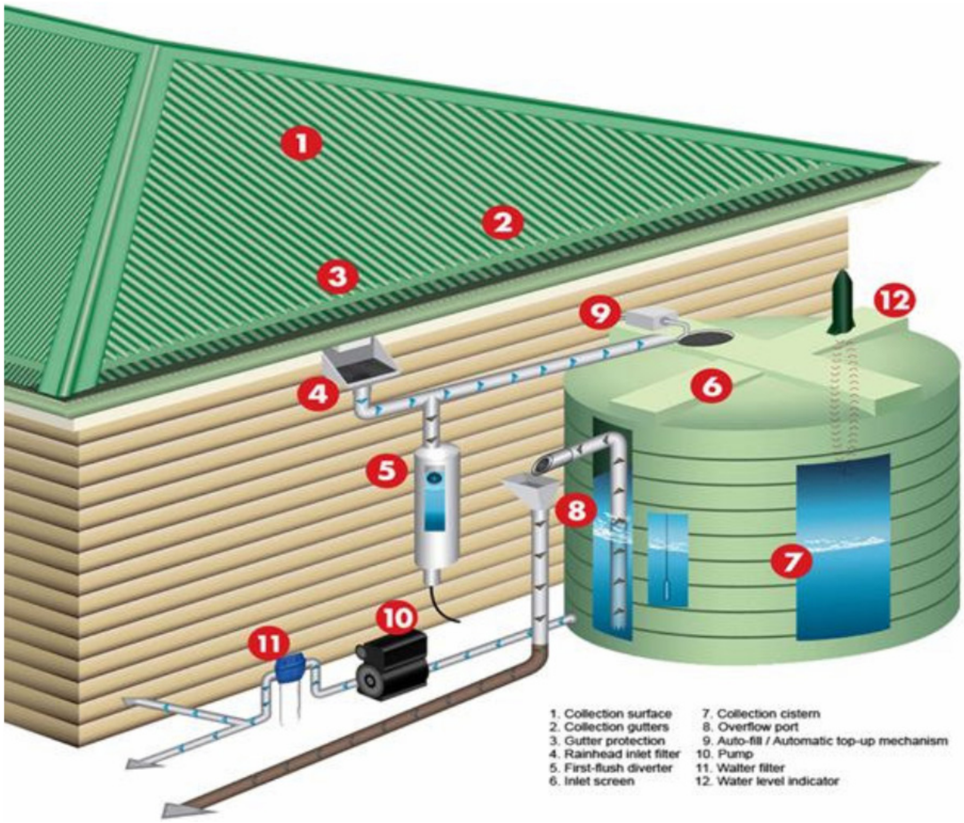

Figure 1.4: Rainwater Catchment System. (Seckin, 2010)

Rushton, B.T. (2001) showed results of a two-year research that took place at the Florida Aquarium in Tampa, Fl from 1998-2000. However, only the first year's data from August 1998 to August 1999 was evaluated. For this study, a modern parking lot was developed to compare three pavement types, as well as basins with and without swales, in terms of decreasing runoff and pollutant loads. The methodology, followed to include the swales in the parking lot without reducing the length of the parking rooms, was by making each parking room 61 cm shorter, so a space of 122 cm would be provided for vegetated drainage depressions between the rooms pulled towards opposite sides. Eight small basins were installed in the parking lot for measuring the quality and quantity of the runoff coming from the different paving types. The parking lot was divided to four treatment systems including typical asphalt paving with no swale, asphalt paving,

with a swale, cement paving with a swale, and permeable paving with a swale (Figure 1.5). The swales were planted with native pasture grasses.

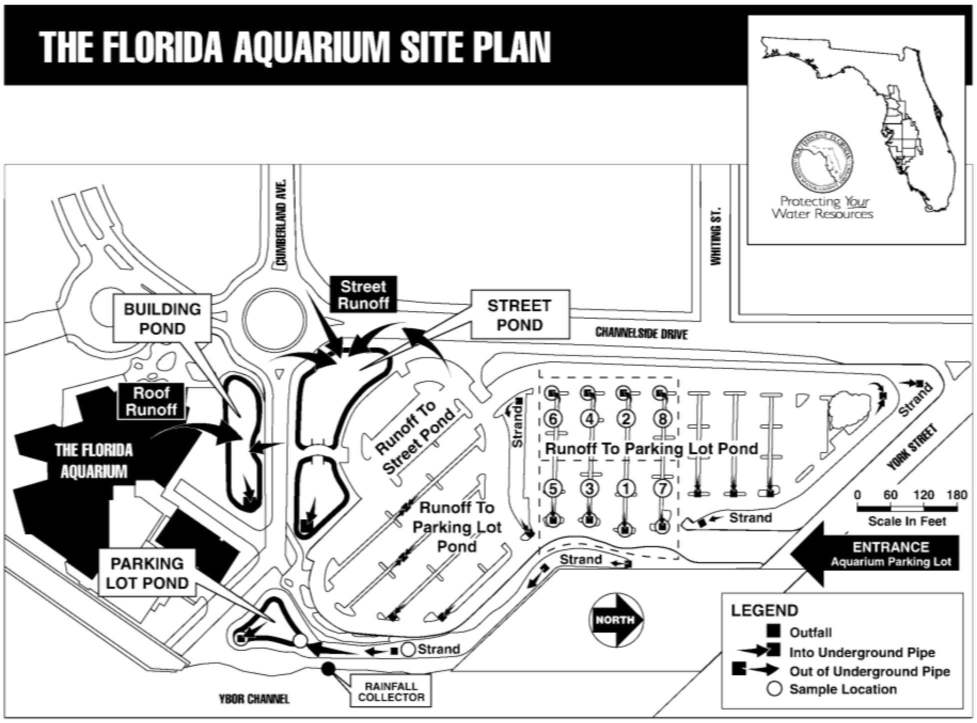

Figure 1.5: Florida Parking Lot Study Site. (Rushton, 2001)

Hydrologically, the performance evaluation of each system was based on the runoff coefficient, which is a value that ranges from zero to one and expresses the fraction of rainfall volume that is actually converted into storm runoff.

Runoff coefficient = (volume discharged) / [(basin size) (rainfall amount)]   (1.4)

According to Rushton, "if all the rain falling on a drainage basin ran off, the runoff coefficient would be 1.0 or 100%".

The runoff quantity results showed that larger vegetated areas (approximately the size of one parking space) account for a runoff coefficient calculation reduction of 40-50% for the

smaller basins. For precipitation events less than 2 cm, basins with swales and pervious pavement have 80-90% less runoff than basins without swales, and 60-80% less runoff than basins with the other pavement types and swales. The percent of rainfall converted to runoff for each treatment system is shown in Table (1.2), and a compression between hydrographs generated by each system shown in figure (1.6). Basins with swales reduce runoff approximately 40% less than the basins without swales even though larger rainfall amounts showed fewer differences in runoff amounts between the different paving types. The high gravel content of 8.9% shown in the soil analysis at the site might be another reason that enhanced the soil infiltration rates. In sum, swales reduced runoff for all rainfall events and paving types. These results display that even little planted areas in parking lots can considerably enhance infiltration rates.

Table 1.2: Total Yearly Flow Amounts, Average Runoff Coefficients. (Rushton, 2001)

			Asphalt, No Swale		Asphalt, with Swale		Cement, with Swale		Pervious, with Swale	
Parameter	LOD	Rain	F1	F2	F7	F8	F3	F4	F5	F6
(a) Hydrology										
Number of observations	—	—	30	30	30	30	30	30	30	30
Basin size (ha)	—	—	0.105	0.105	0.097	0.105	0.093	0.105	0.093	0.105
Total runoff (m^3/ha-year)	—	—	5114	4290	1652	3130	2320	3154	1172	2137
Average runoff coefficient	—	—	0.58	0.51	0.16	0.35	0.22	0.33	0.10	0.20

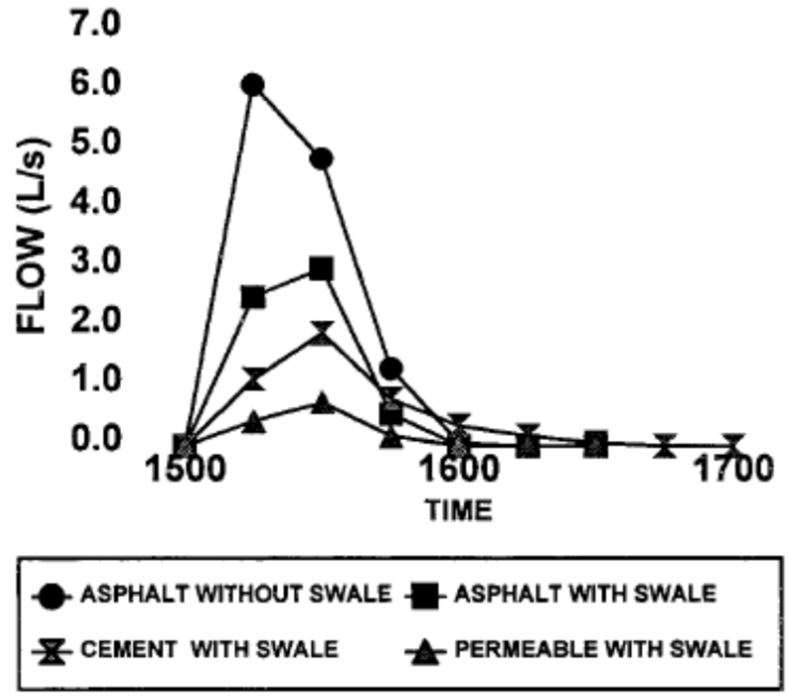

Figure 1.6: Hydrographs Generated by Each Treatment System. (Rushton, 2001)

Miller, C. (1998) explained in his study that vegetated rooftops offer a practical solution for controlling runoff at the source mainly for older American cities, which are suffering from trouble flooding on roads and walkways and chronic overflows of connected sewer systems. A vegetated roof cover is a thin layer of living vegetations installed on top of a conventional roof. Combined green roofs can imitate natural hydrologic process and can reach the same runoff characteristics of pre-developed areas. Green roofs consist of three components, which are subsurface drainage, growth media, and vegetation.

The project was implemented in Philadelphia, Pennsylvania. A 3,000 sq-ft rooftop was fitted with a vegetated rooftop. The performance goal was to achieve the predevelopment runoff peak rates for a 24-hour, 2-year return-frequency storm. The vegetated roof installed was only 3.4 inches thick, including the drain layer (Figure 1.7).

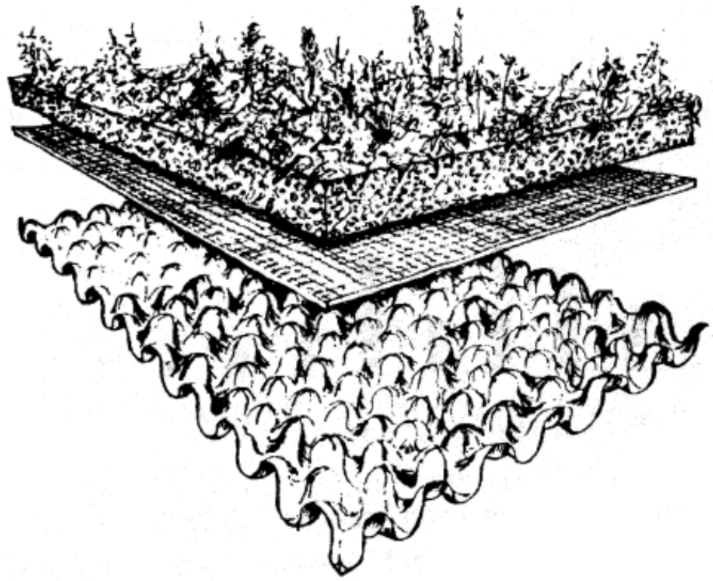

Figure 1.7: Structure of the Philadelphia Vegetated Roof Cover. (Miller, 1998)

With a saturated infiltration capacity of 3.5 inches per hour, maximum saturated weight of the vegetated is less than 17 lb/ft^2; on the other hand, it weighs less than 5lb/ft^2 when dry. No extra foundations or any other structural support were required for installation. The artificial subdrain layer plays a very important role in the system where it promotes rapid water drainage from the roof surface. It is composited of thin, lightweight growth media appropriate for installation on existing roof surfaces. Moreover, it can withstand with seasonal conditions typical of the zone.

Prior to the preparation of this paper, too few storms had been observed to evaluate the quantity of recharge flowed out from the vegetative covered roof. Data was obtained from one strong storm monitored during a 0.4 inch, 20-minute rainfall event (Figure 1.8). Additional data from a pilot-scale experimental station was used in this study. The experienced data showed that runoff generated from storms, with less than 0.6 inches, was small enough to be ignored. Within a 9-month period, only 15.5 inches of runoff was generated from 44 inches of rainfall recorded at the pilot-scale test station. Runoff occurred for precipitation events between 0.6 and 1.0 inches,

but lagged rainfall significantly. The study shows further benefits of this project including extended life of the underlying roof materials, and reduction of energy costs by improving effectiveness of insulation and restoration of ecological aesthetic value of open space in densely populated areas.

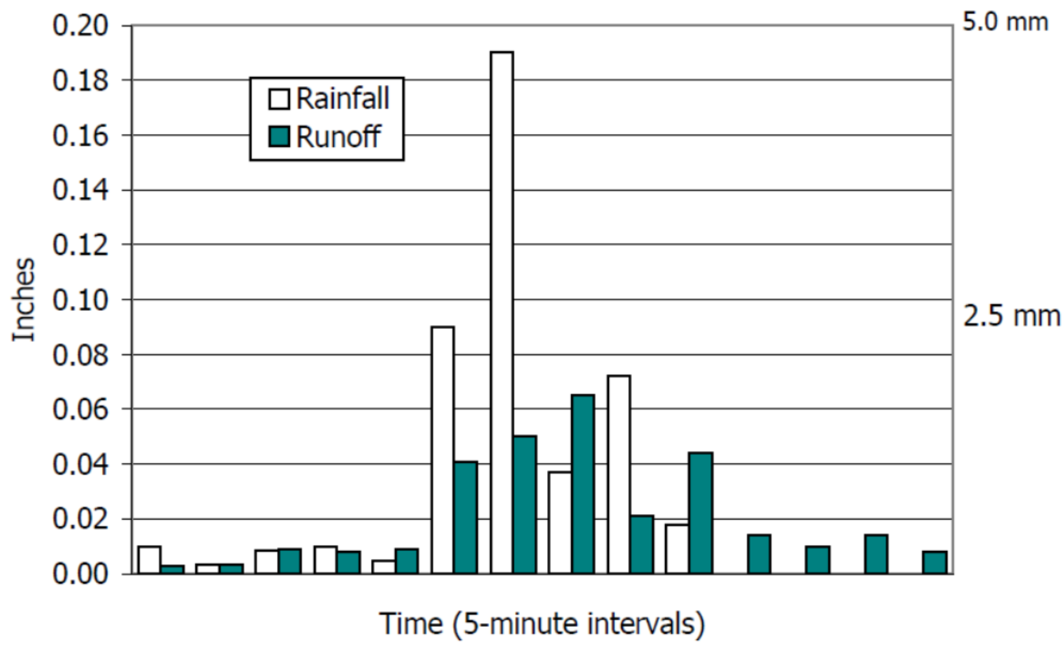

Figure 1.8: A Rainfall Event of 0.4 Inches with Saturated Media. (Miller, 1998)

Davis, A. (2008) discussed the results of a research conducted on two parallel bioretention cells, installed in the University of Maryland campus, to capture and treat storm water runoff captured from a 2400 m^2 adjacent parking lot. The cells had the same structural characteristics where they have the same volume with 2.4m width, 11 m length, and 0.9-1.2 m depth and were filled with the same media, which consisted of engineered soil volumetric mix with 50% sand, 30% topsoil, and 20% compost with less than 10% clay. The media layer (figure 1.9) was covered with a thin layer (2.5–8 cm) of standard hardwood mulch. Selected small trees, shrubs, and grass were established in the bioretention cells, even though the priority was for the shrubs because the tress performance was worse.

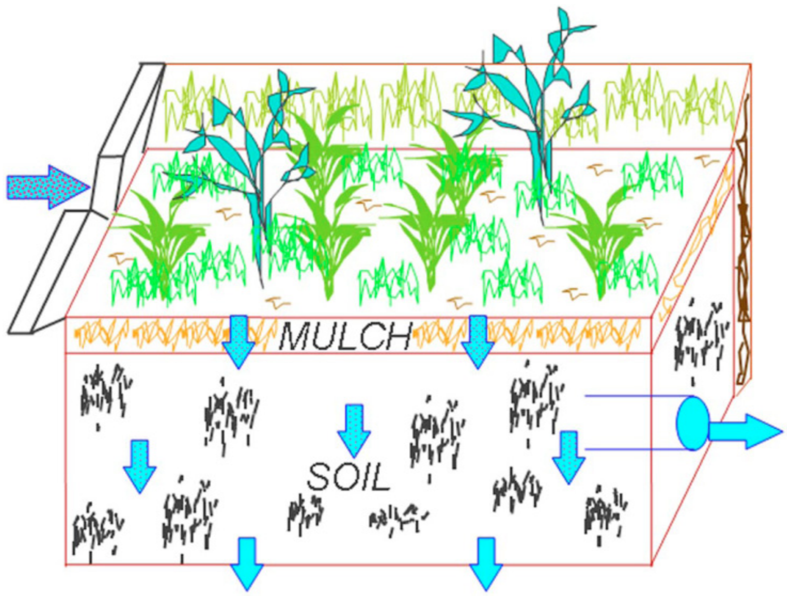

Figure 1.9: Diagram of Bioretention/Rain Garden. (Davis, 2008)

The flow was conveyed from the parking lot via concrete splitters and was equally divided among the two bioretention cells. The underdrains of the bioretention facilities were captured and transmitted by a 15 cm perforated plastic pipe to small first order stream (Campus Greek) running through the University of Maryland campus (figure 1.10).

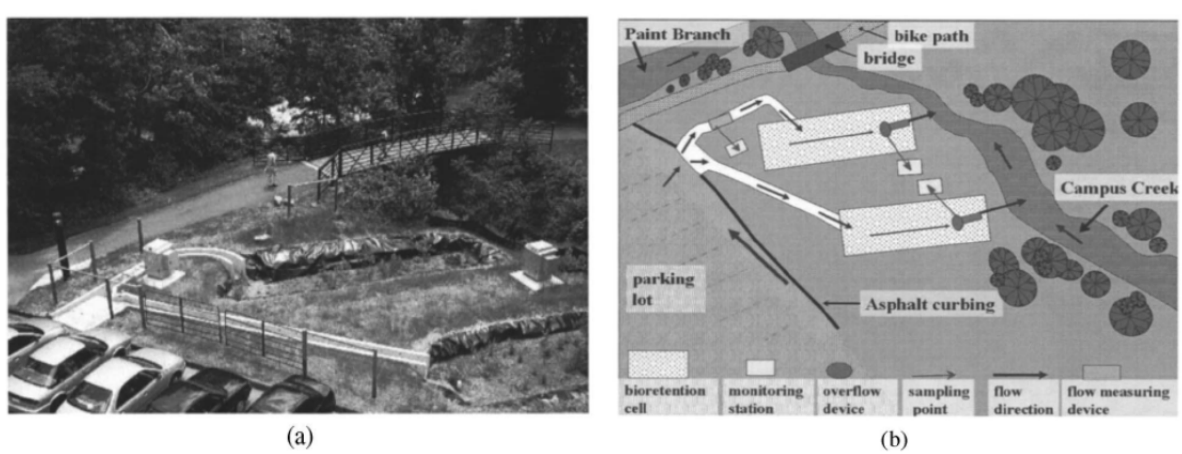

Figure 1.10: University of Maryland, College Park Bioretention Site Diagram. (a) Aerial Photograph. (b) Stormwater Runoff Flow Path. (Davis, 2008)

Data of 49 rainfall events was monitored and used to evaluate the performance of the two bioretention cells. The evaluation was based on comparing the flow volume, peak flow, and peak delay between the developed and undeveloped area. The inflow and the outflow rate, during storms, were measured by flow meters and runoff flow was calculated.

The results of this study showed that these bioretention systems significantly reduce the hydrologic impacts of the runoff at its source. Outflow was not observed in 18% of the 49 monitored events, meaning that much of the runoff was captured and retained in the media (figure 1.11). In big storms, there was observed outflow which was flowing in low flow rate and continued for many hours for several days leading to reduce the flow peak by 44-64% and delay it by a factor of at least 2 times.

The project aimed to reduce the 24hr event volume, the peak flow by 33%, and peak flow delays by a factor greater than 6. The goals were successfully achieved where the first bioretention cell produced 55%, 30% and 38% reduction for the flow volume, peak flow, and peak flow delays respectively. As for the second cell, the results were 62%, 43%, and 31% respectively.

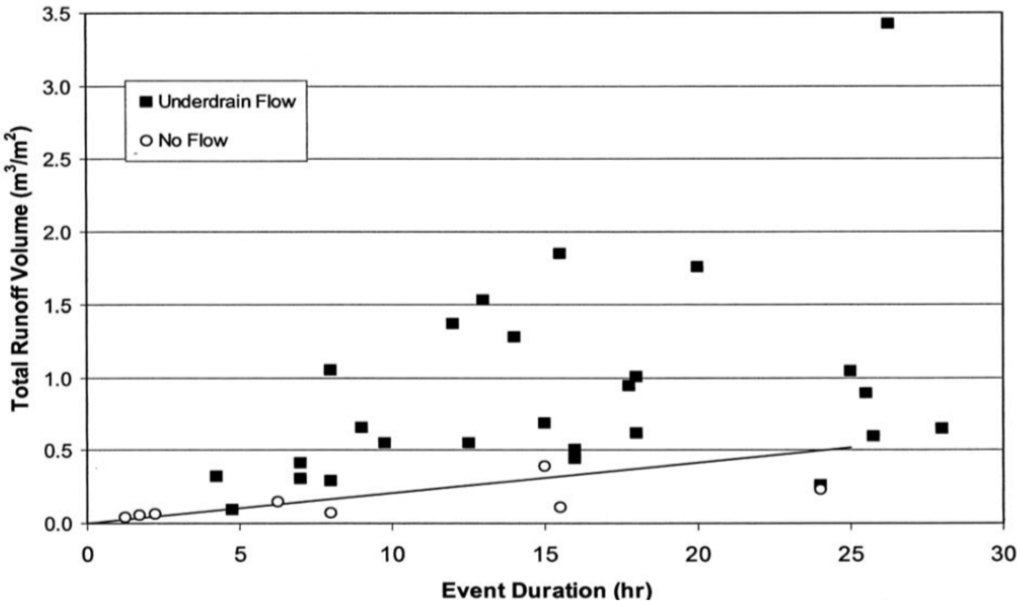

Figure 1.11: No Underdrain Flows Produced in the Bioretention Cells. (Davis, 2008)

Booth, D. at el (1996) studied and evaluated the performance of impervious asphalt surfaces in reducing the runoff volume and pollutant loads and enhancing the infiltration rate. The research took place in a parking lot constructed especially for this study and located at the southeast corner of the King County Public Works facility in Renton, Washington. In addition to a controlling stall with conventional asphalt surface, eight stalls with different pavement types were installed. The pavement types included a plastic network with grass infilling, an equivalent plastic network with gravel infilling, impervious cement blocks with grass infilling, and impervious blocks with gravel infilling. The percentage of impervious area for each pavement type was less than 5% for the former two types and about 60 and 90% for the last two types, respectively. The storm runoff quality and quantity were measured and analyzed by collecting the water via pipes laid six-eight inches below the pavement surface of each stall.

The result of analyzing the data of three monitored storm events during the autumn of 1996, used to evaluate the various impervious pavements, showed that the volume of runoff

generated from cement blocks with 60% impervious surface stalls and runoff from traditional asphalt are compared (Figure 1.12). Also, throughout the duration of the event, the storm had a moderately uniform distribution of rainfall of 4mm per hour. Rain fall on the asphalt produced a high total volume of runoff and sharp hydrograph peaks. The cement blocks with 60% impervious barely generated one peak per hour, which is about 0.03mm per hour of runoff. This data is representative of data collected at the other stalls and reflect little or no runoff from the impervious pavement stalls.

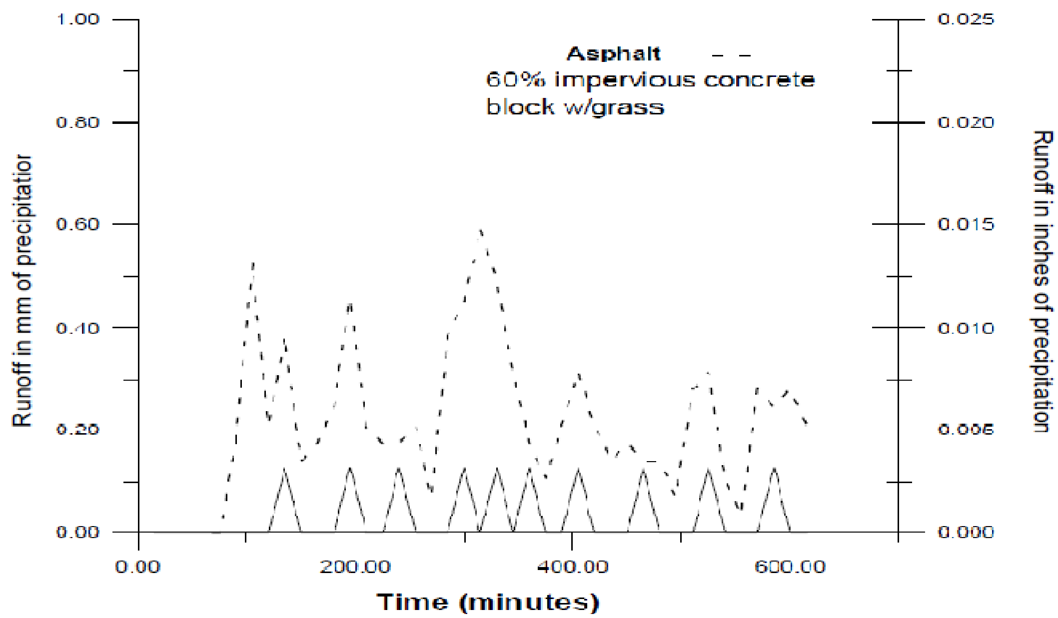

Figure 1.12: Runoff From 60% Impervious Pavement vs. Asphalt. (Booth, 1996)

On the other hand, and as for the asphalt surface, high peak flows corresponding with precipitation amounts indicated that the amount of runoff generated on the asphalt responded rapidly to changes in the rate of rainfall (Figure 1.13).

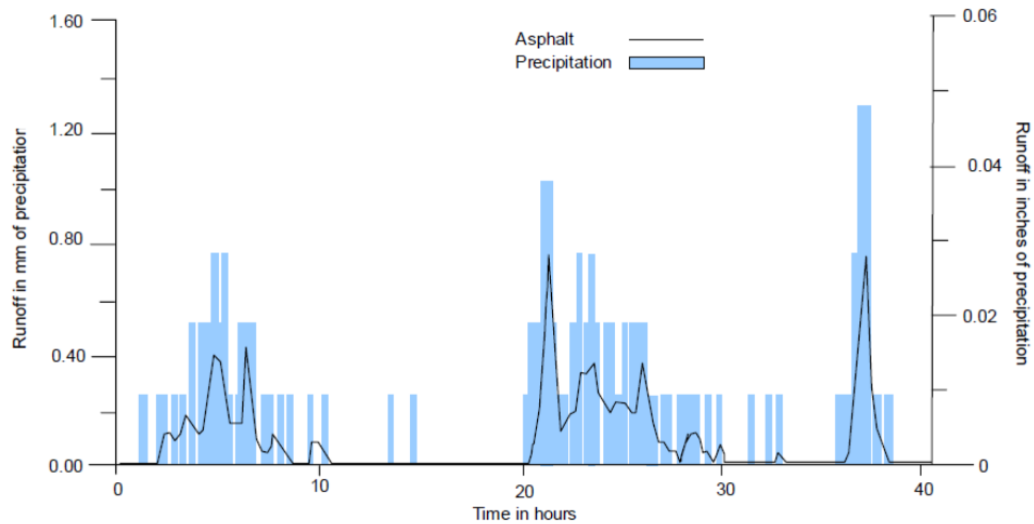

Figure 1.13: Surface Runoff from Asphalt Compared to Precipitation. (Booth, 1996)

Pierce County Low Impact Development Study, 2001, studied the possibility of installing Low Impact Development (LID) devices in Pierce County as an alternative strategy to conventional stormwater control practices. Two residential developments in addition to a 12500 square foot single family house were used to compare the two systems. The comparison was conducted in terms of reduction of the runoff volume, enhancement of water quality, and the implementation and life cycle cost. The LID techniques used on each site included reducing lot size, increasing buffers and preserving open space, reducing street width and impervious surfaces, using grasscrete underlain with gravel for parking and temporary storage of stormwater, amended soil for increase the infiltration rate, and reuse of rooftop runoff for non-potable uses on-site. On the other hand, the designed conventional system included a curb and gutter storm drain system with detention ponds. The LID system aimed to reduce the impermeable surface area in the two residential developments, Kensington Estates and Garden Valley, from 30% to 7% and from 23% to almost 0% respectively. As for the single family lot, the stormwater was

collected for non-potable uses such as toilet and dishwashers; therefore, a rooftop water catchment system was planned for this purpose.

For the hydrologic analysis, a single event was used to model four systems with different conditions for the same site in Kensington Estates. These assumed systems included pre-developed site covered by mature forest with some wetlands, the site with existing condition of pastures replacing some of the forest, conventional development where the site is almost entirely devoted to single family homes and yards and stormwater is collected via pipes and catch basins and treated in a stormwater pond, and LID development where identical housing density is achieved but forested open space replaces much of the lawns and storm water is treated throughout the site as close to the source as possible. Figure (1.14) indicates the result of this modelling where the site with the LID system reduces the peak runoff to a value very close to the pre-developed condition system while the conventional developed system increases the peak flow to a value much higher than the existing condition system, which is itself higher than the LID system.

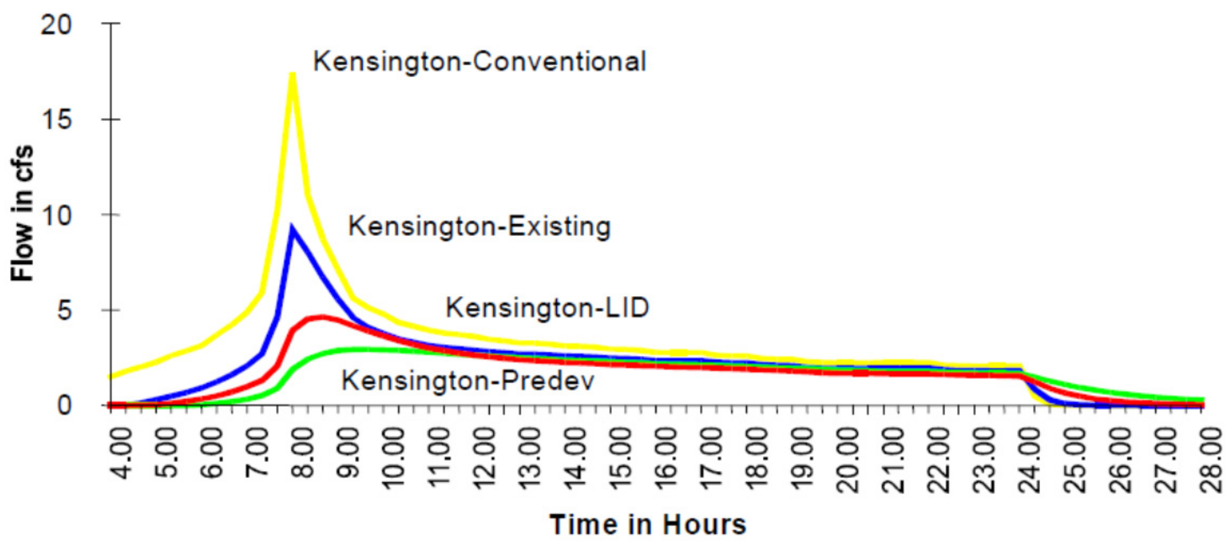

Figure 1.14: Hydrograph of Runoff from Four Scenarios for Single Storm Event. (Pierce County LID Study, 2001)

The result of cost analysis showed that LID can be a cost-effective solution for Pierce County developers. Costs for the Kensington Estates LID design were more than the conventional design, with the rooftop collection system being the major factor in this difference. Without the rooftop collection system, the LID and conventional costs would have been about the same. However, for the Garden Valley designs, the LID costs were about $60000 less than the conventional costs. Some of the LID applications, such as the rooftop collection system and the grasscrete parking, are more expensive than other practices and were employed because of the poor soils and limited land available.

2. The Methodology of LID and Landscape Design for a Single Family Residence

2.1 Introduction

When the land surface is converted from rural to urban conditions, stormwater runoff will increase because of the greater amount of the impermeable area at the site. In this chapter, methodology of Low Impact Development (LID) practices design process for a single family lot is described in detail. The idea of the design is to keep hydrologic characteristics of the watershed as they were prior to development. Small-scale of LID practices including bioretention cells and vegetated swales are combined to form an Integrated Management Practices (IMP) system. The practices are distributed over the lawn area of the house in order to capture the stormwater runoff at the closest point to the source and provide as much stored water for plants as possible. This strategy slows down runoff, reduces flow rates from the site, and increases infiltration. Moreover, the management of the stormwater runoff at the site decreases the need of the conventional management practices downstream. Meanwhile, the captured water is stored in the soil and then used by the plants, which have an excellent drought tolerance and appropriate for designing a passive rainwater harvested landscape. For this design, 20 years (from 1991 to 2010) of historical temperature and precipitation data was used to adapt the design to the arid condition of Desert Southwest represented by El Paso, TX, Albuquerque, NM, and Phoenix, AZ. The design is based on the Low Impact Development Manual (13514UFC 3-210-10), Urban Hydrology for Small Watersheds Manual (TR-55) and Xeriscape Landscape Water Conservation B-1584 5-01. However, some modifications are conducted on the LID practices in order to minimize the construction and the maintenance cost.

2.2 The Model House: Location and Conditions

In order to generalize the design, the house could be placed at any location in El Paso, Albuquerque, and Phoenix. However, for this design the house is located in the area where the soil is deep loamy soil because according to the Jaco, H. B., 1971 and1977, and Hartman, G. W., 1977, this kind of soil dominates a large area of the three selected cities. A real house plan (figure 2.1) is used to mimic any constrains, such as a limited lawn area and/or house roof subdivisions, may be encountered. AutoCAD 2010 was used to draw the house plan. It, also, was used to measure the runoff capture area and all other measurements necessary for the design.

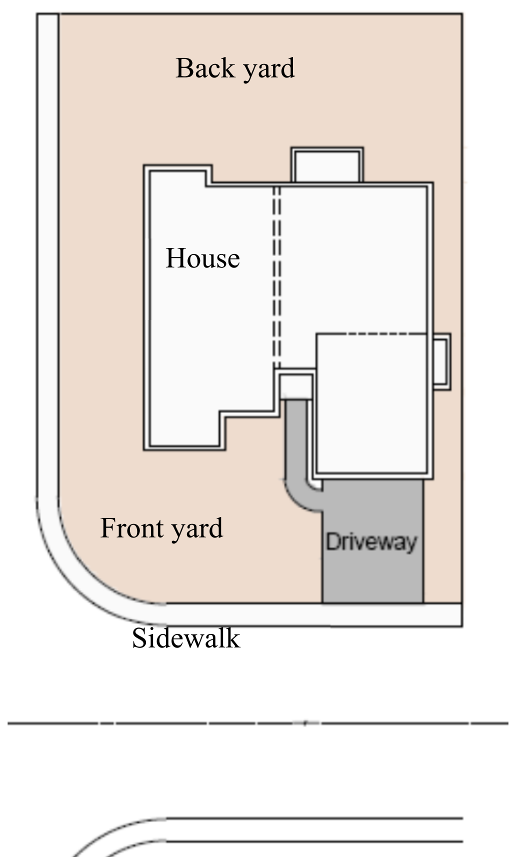

Figure 2.1: The Model House Plan.

The evaluation of the site condition will facilitate LID design development by providing site details that assist in the development of Integrated Management Practices. However, some conditions are generalized to comply with open house location. For these particular sites in the three cities, groundwater table is assumed to be 75 m (250 ft.) which is deep enough to be ignored (Jaco, H. B., 1971 and1977, and Hartman, G. W., 1977). The soil in the area is deep, loam or sandy loam, soil with moderate infiltration rates. There is an existing stormwater drainage system that collects the runoff from the streets and conveys it to a conventional stormwater management facility.

2.3 The Selection of LID Practices and Locations

To design an Integrated Management Practices (IMP) system, the house is broken a series of small drainage areas (watersheds). According to the United States Environmental Protection Agency (EPA), a watershed is the area of land where all of the water that is under it or drains off of it goes into the same place. The lot is divided to six watersheds where LID practices will be installed in each area to capture the runoff at the closest possible point to its source, and also to provide storing water spots for plants. The number of watersheds into which the house should be divided depends on stormwater runoff paths, which are controlled by the slope direction of roof subdivisions, driveway, the sidewalk, and the street.

For this study, the direction of the runoff paths are shown in figure (2.2), with an assumption of that the driveway and the sidewalk in front of the house are sloped toward the front yard of the house.

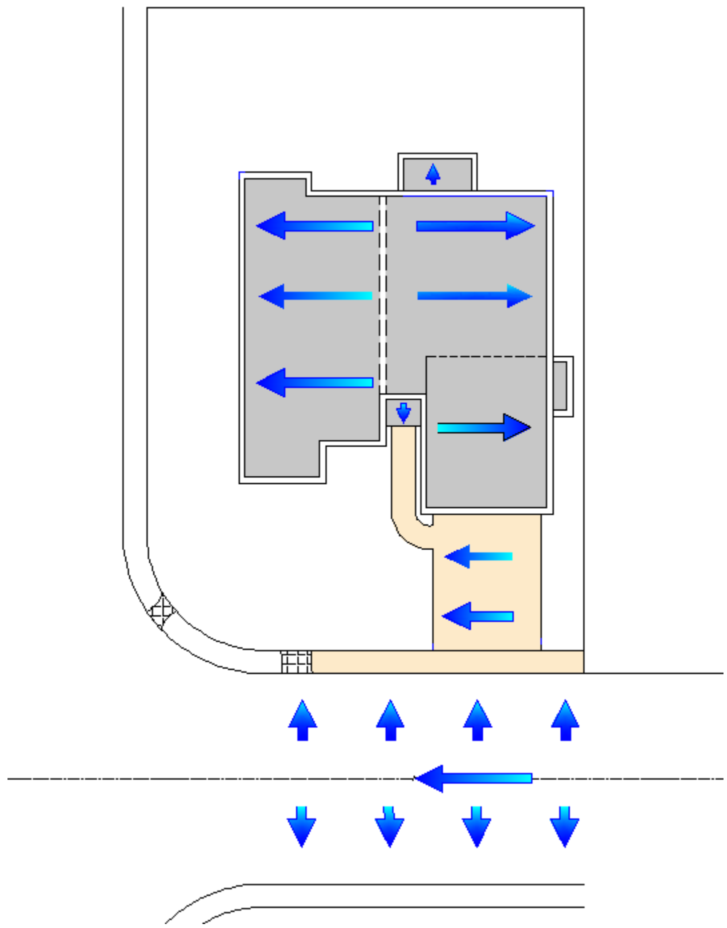

Figure 2.2: Runoff Paths.

After determining the runoff paths, two options for watersheds' subdivision are taken into consideration. The first option (lot), shown in figure (2.3), the runoff generated by the house roof, the driveway, and the sidewalk is captured

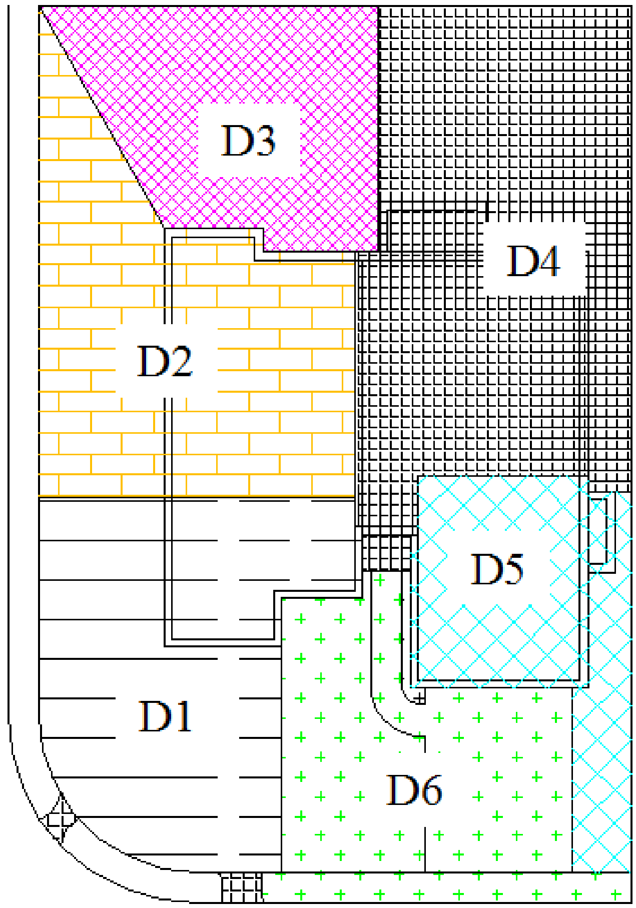

Figure 2.3: Option-1 (Lot) for the Drainage Area Subdivisions.

The second option (lot + street), shown in figure (2.4), includes, in addition to the components of option-1 , the half of the street along the front side of the house, assuming that the street is divided to two equivalent halves, and every half is sloped (crowned) toward the adjacent sidewalk and house.

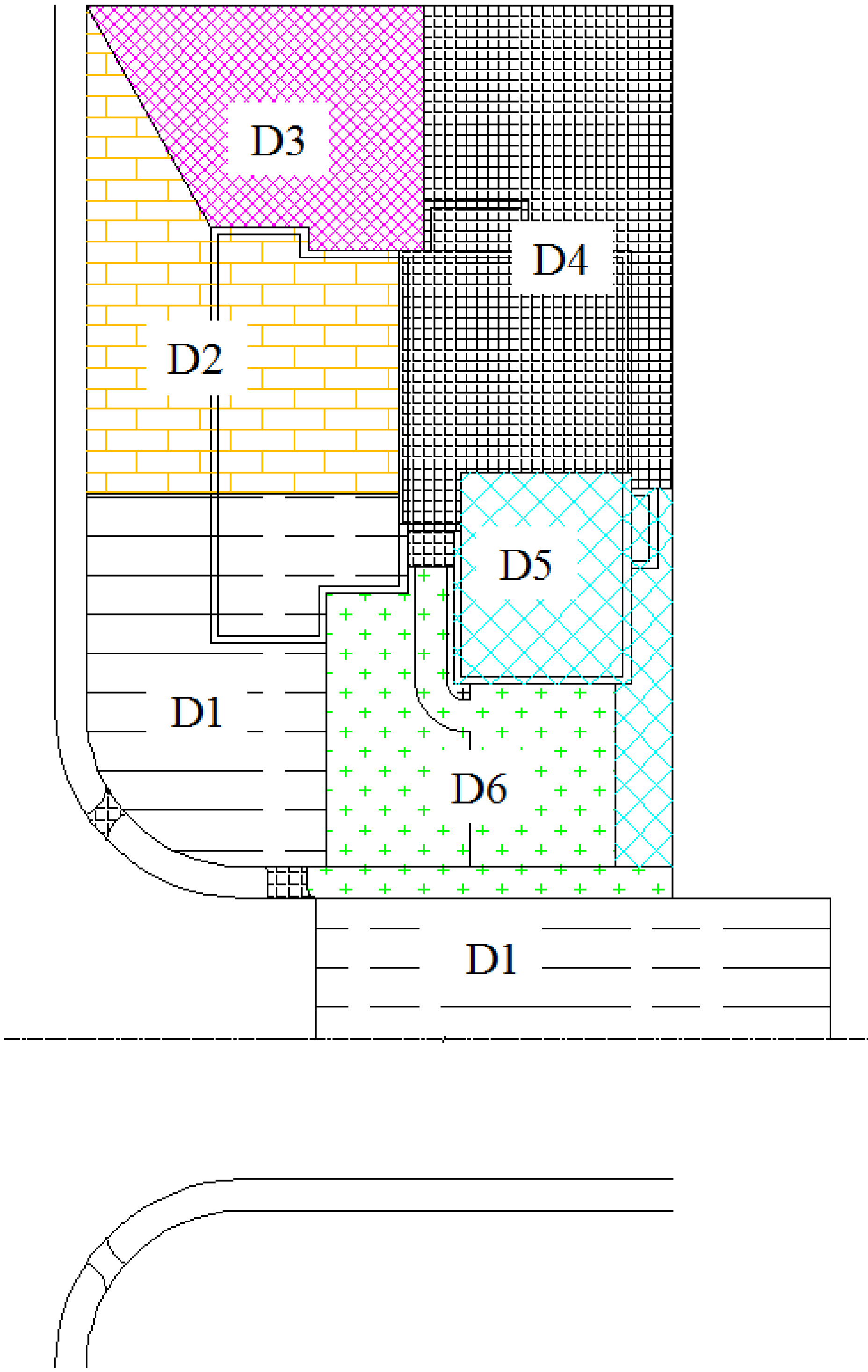

Figure 2.4: Option-2 (Lot +Street) for the Drainage Area Subdivisions.

For placing any LID practices, some regulations should be taken in consideration. The regulations include:

- LID practices should be placed at least 10 feet away from buildings to prevent moisture into basements.
- LID practices should not be placed over a septic tank or leach field.
- LID practices should not be placed near a drinking water well to prevent any contaminant seepage.
- Care should be taken when digging the soil to avoid damaging any existing tree roots.
- Safe distance from any existing buried facilities, such as water pipes, should be considered.
- Property setbacks have to be met, so verification with the city should be done before placing the LID practices.

Four LID practices are selected to be installed for this particular IMP system: bioretention cell, vegetated swale, French drain, and gravel mulch. Since the soil has a moderate infiltration rate with an average of 5.4 inch/day (Roberson et al, 1997), the soil is able to infiltrate the water into the ground, so there is no need for underdrains or overflow pipes. However, the lawn area would be contoured to be gently sloped toward the street, and the bioretention units are sloped toward each other and connected by French drains, so in large storms, when the stormwater runoff excesses the infiltration rate and floods the yard, the water will be transmitted by the French drains from a unit to another, and finally to the street where it can be captured by the municipal drainage system. In order to insure that the runoff generated in each watershed will be captured by the LID unit designed for it, the yard in this watershed has to

be gently sloped toward the unit or toward the French drain that linked to it (figure 2.5). However, this step will not conflict the general slop of the yard toward the street.

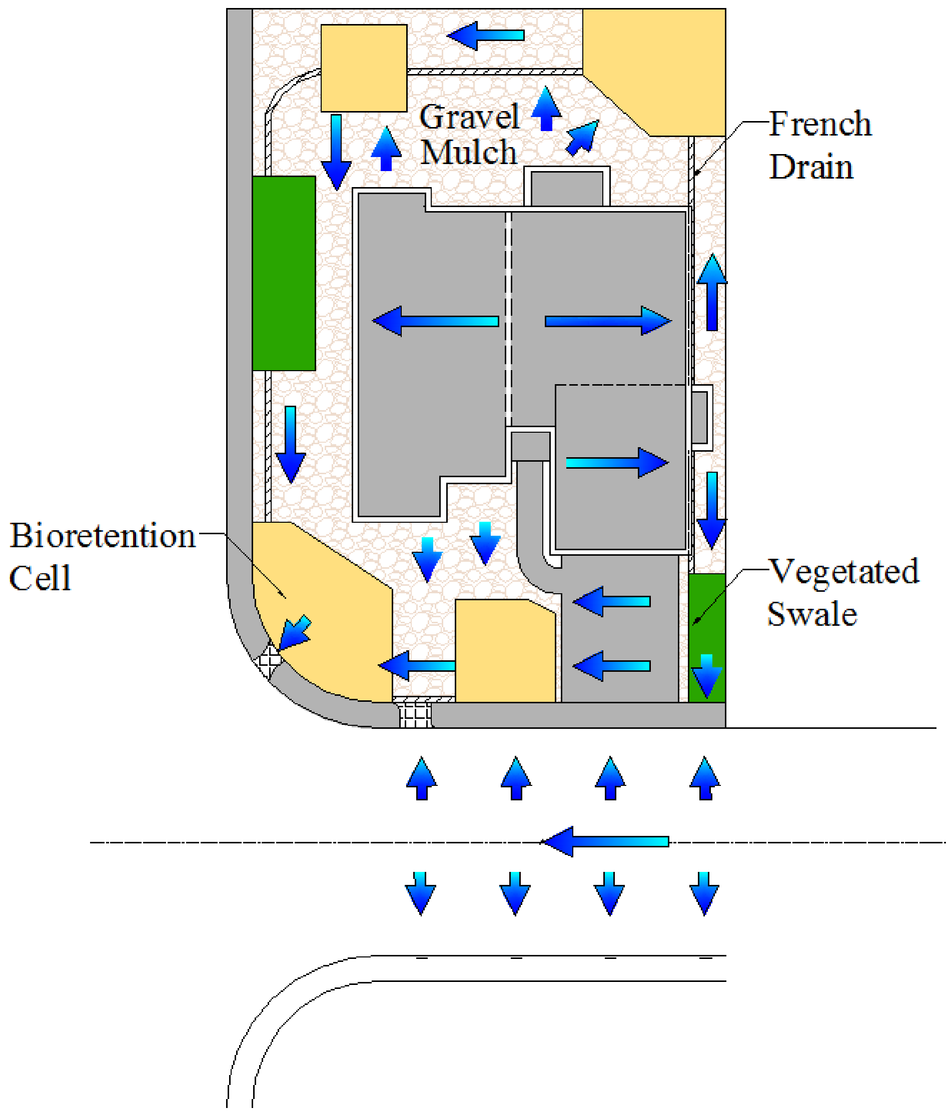

Figure 2.5: Locations of LID Practices and Flow Path.

2.3.1 Bioretention Cells Design

As mentioned before, there is no need for underdrains, the design is simplified where the excessive flow is transmitted under gravity force to the next bioretention by French drain until all units are not capable of retaining the runoff, and then the water would be passed to the street. The Bioretention cell, figure (2.6), has high porous backfill under the vegetated surface. The upper six inches of the porous backfill is sorted coarse gravel, with an effective porosity of about 30%, through which water can soak into the lower six inches at a high infiltration rate (more than 0.3 inch/hr) fine sand with an effective porosity of 33% (Fetter, 2000). Permeable plastic screen is installed between the two layers for prevention of weed growth. Temporarily storing the water in the porous gravel during infiltration eliminates concerns about safety and vectors (e.g. mosquitoes). The bioretention edges are slope by 1:2 to control any erosion that may be caused by the flow.

2.3.2 Vegetated Swales Design

The function of the vegetated swale is the same as the bioretention cell. However, it is selected to be installed in the watersheds 2 and 5 because of the limited widths in the lawn area. To deal with this width limitation, the storage capacity of the swale has to be higher than that in the bioretention cells. Therefore, the fine sand layer backfill is 3.6 inches thicker than in the bioretention cells (figure 2.7).

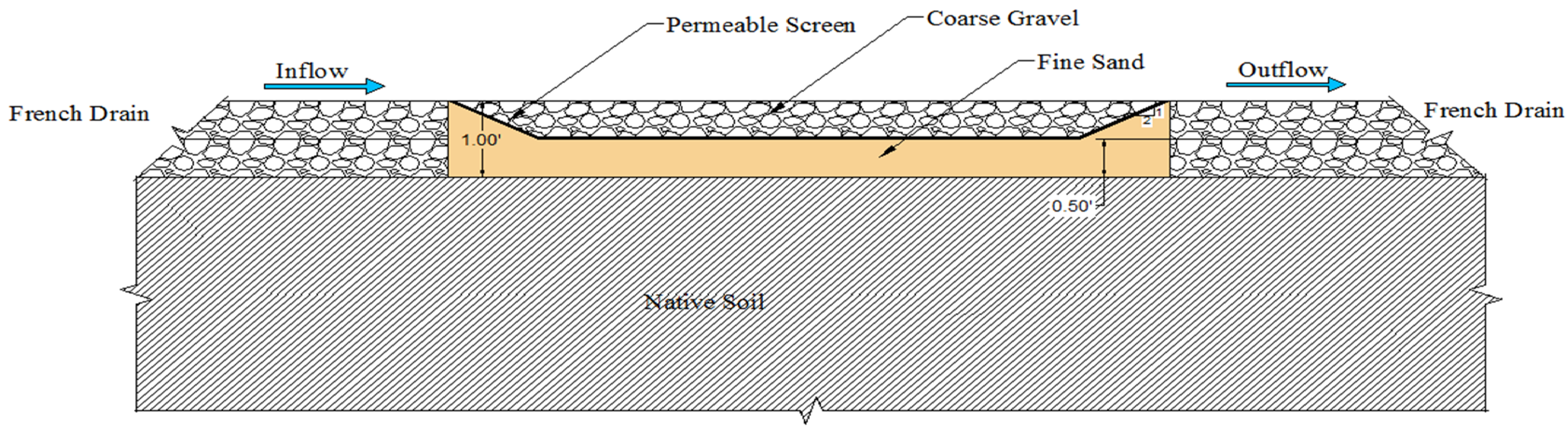

Figure 2.6: Cross Section of a Bioretention Cell.

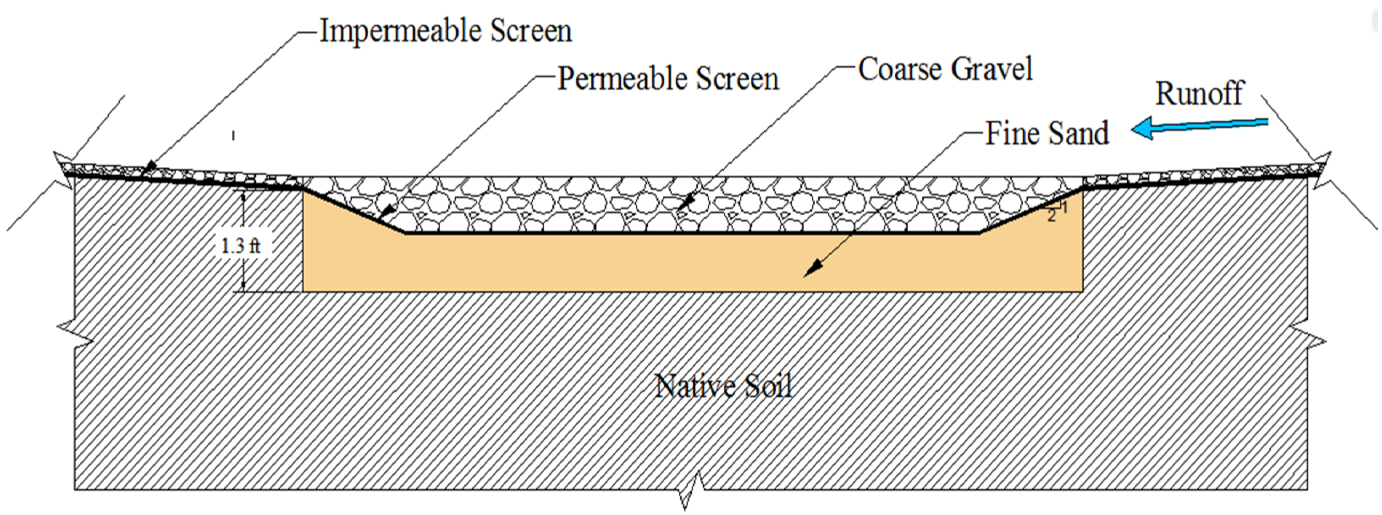

Figure 2.7: Cross Section of a Vegetated Swale.

2.3.3 French Drains Design

French drains are an important component in this Integrated Management Practices (IMP) system. The French drain line, figure (2.8), consists of simply lined trenches filled with sorted coarse gravel and gently sloped to transfer the water to and from the bioretention units. The design is simplified where no pipes are used in order to reduce the cost and to facilitate the operation process. The French drains are 1 foot deep and 1 foot wide. Perforated plastic is installed in the middle for reduction of water evaporation, and impermeable plastic surrounds the trench for prevention of weeds growth and to prevent the water from infiltrating into the soil in this area where no plants are grown.

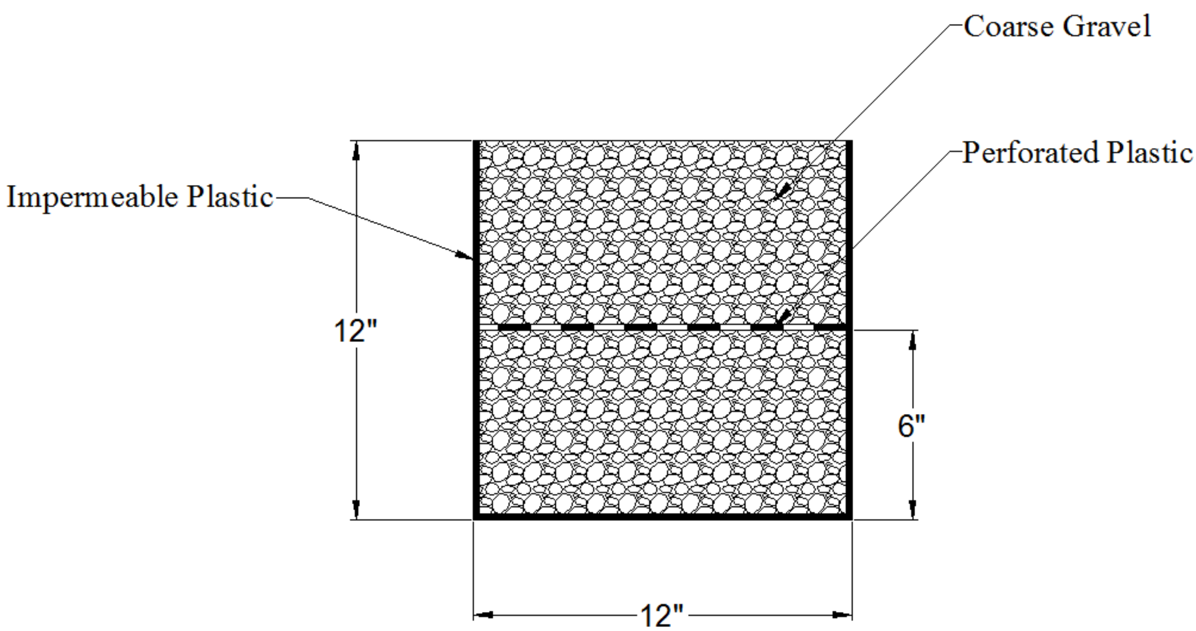

Figure 2.8: French Drain Cross Section.

The French drain line has more than one role to play in this (IMP) system: 1) Absorbs the water of the drip line from the roof, (figure 2.9), and conveys it to the bioretention units. 2) Passes through the yard and connects the bioretention units to each other to forward the overflow

from the flooded units to the next one and then to the street. 3) Collects the runoff from the areas adjacent to the line, which are gently sloped toward it, and transmits it to bioretention units.

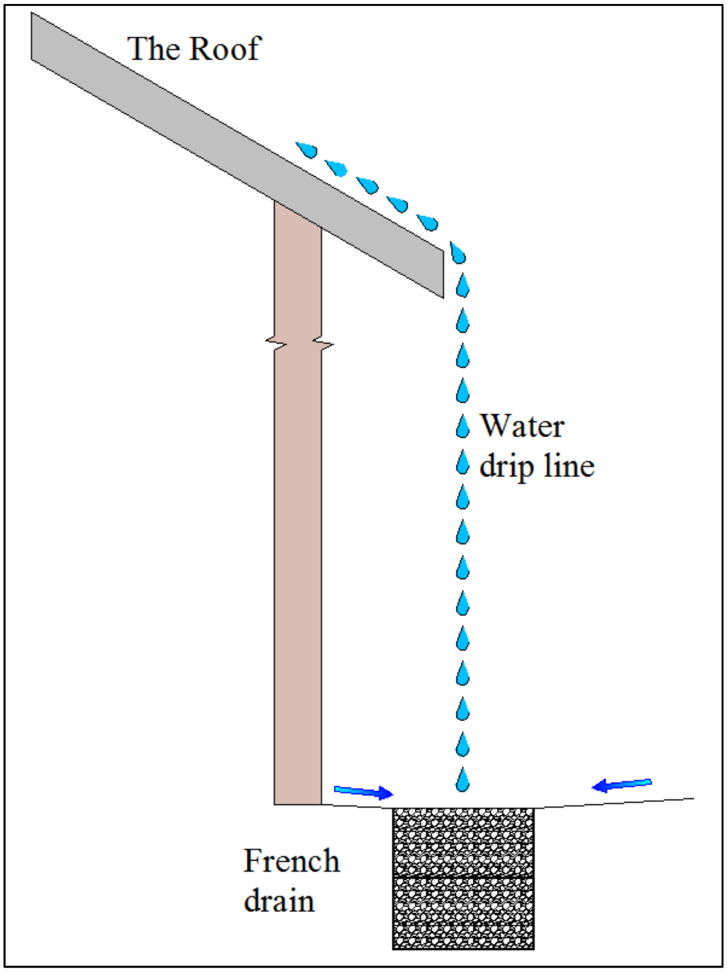

Figure 2.9: French Drain Function.

2.3.4 Gravel Mulch Design

The remaining area in the lawn, after contouring the surface and implementing the other previous IMP components, is covered by mulch. Usually, mulch consists of pervious weed barrier covered by 1 to 2 inches of gravel or coarse sand. However, pervious weed barrier is replaced with impervious one this design in order to capture more water from the spots in the yard other than the bioretention units (figure 2.10).

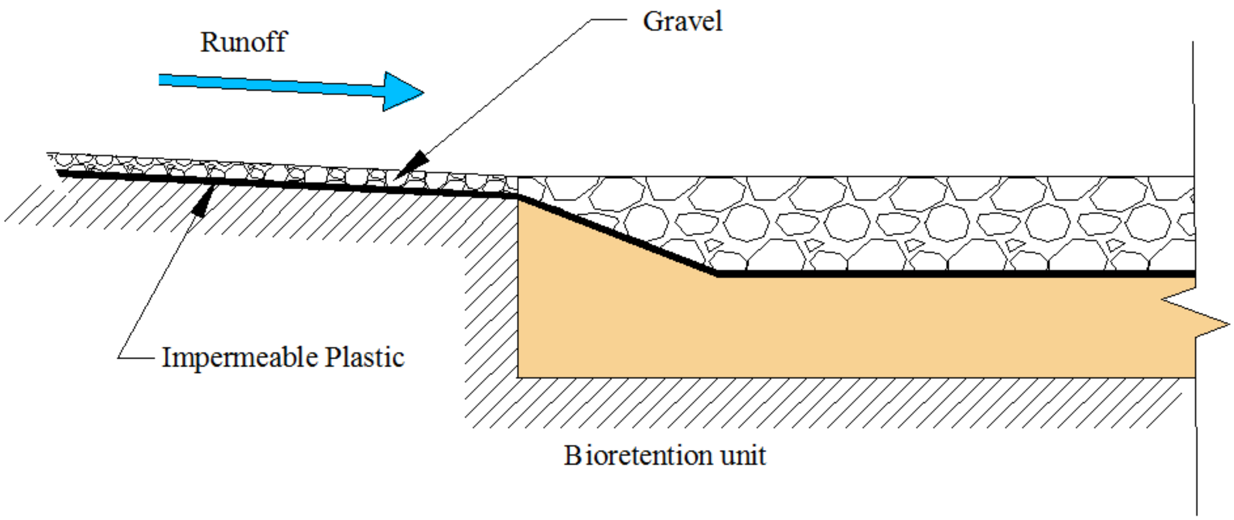

Figure 2.10: The Implemented Mulch Sloped toward a Bioretention Unit.

2.4 Size Determination of Bioretention Cells

As mentioned before, the design aims to capture the excessive runoff that results from the change of the site surface conditions. A method was developed to estimate the pre and post development runoff based on the Runoff Curve Number (SCS) method which is described in the TR-55 manual. This method basically depends on major factors including the hydrologic soil group (HSG), cover type, treatment, hydrologic condition, and antecedent runoff condition (ARC).

2.4.1 Estimation of Runoff Volume

The following equation is used to estimate the runoff:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad (2.1)$$

Where:

Q = runoff (in)

P = rainfall (in), 20 years of historical data is used.

S = potential maximum retention after runoff begins (in) and

I_a = initial abstraction (in).

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation:

$$I_a = 0.2S \tag{2.2}$$

S is related to the soil and cover conditions of the watershed through the Curve Number (CN). CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \tag{2.3}$$

The value of curve number (CN) reflects the degree to which land surface conditions will generate runoff. This value can be determined by following steps in the TR-55 manual. For any developed site there will be more than one type of surface covers; therefor, the following equation can be used to estimate the composite curve number (CN) for the site:

$$\text{Composite CN} = \frac{(A_1 * CN_1 + A_2 * CN_2 + A_3 * CN_3 \ldots\ldots\ldots\ldots A_n * CN_n)}{(A_1 + A_2 + A_3 \ldots\ldots\ldots\ldots A_n)} \tag{2.4}$$

Where

A_1, A_2, A_3 ....A_n the surface covers areas in the site,

And CN_1, CN_2, CN_3.............CN_n are the curve numbers for these areas respectively.

For this study, the soil type is assumed to be loam soil, so the soil hydrologic group is B (Roberson et al, 1997). The pre-development soil cover is assumed to be desert with poor natural landscape of shrubs and grasses, and three different surface cover types included for the post-development surface:

Table 2.1: Curve Number for the Different Surface Covers. (USDA, 1986)

			CN
Surface Cover	Pre-development	Desert with poor natural landscape of shrubs and grasses.	77
	Post-development	Paved street, roofs, driveways, and sidewalk	98
		gravel mulch with impervious weed barrier	96
		Highly porous 1ft layer of gravel and sand (the surface of the bioretention units)	0*

* Because of the high porosity, precipitation that falls herein will be absorbed, so no runoff will be generated.

When CN is determined, the runoff size will be calculated by:

$$V = Q * A \tag{2.5}$$

Where

V= runoff volume (acre-in)

Q= runoff (in), and

A = watershed area (acre)

To size a bioretention unit, the depth (d) should be assumed first based on the backfill material and the available space in the lawn. The backfill material should have a high infiltration rate and a high porosity.

The following balance equation is used to determine the volume of any bioretention cell to take the excessive runoff subsequent from the change of pre-development to post-development conditions.

(Post-development runoff volume – Pre-development runoff volume) = Bioretention volume (2.6)

$$\text{Bioretention volume} = A_s * \varphi * D \tag{2.7}$$

Where

A_s = Bioretention surface area (acre).

φ= Backfill porosity (%), and

D = Bioretention cell depth (in)

2.4.2 Simulation of Sizing the Bioretention Units

To calculate the size of each bioretention unit at each watershed, daily precipitation data for twenty years (from 1991 to 2010) was used. The simulation was conducted using an Excel spreadsheet for each watershed. An adjacent table (Table 2.2) in the same spreadsheet was prepared to contain all of the constant parameters including the area of each surface type in the watershed, the backfill porosity, and the assumed depression depth. These parameters can be changed based on the properties of the watershed and the design. The spreadsheet then converts units as necessary and calculates other properties: the curve number (CN), S, the initial abstraction, combined post-development curve number, S, and initial abstraction. In the spreadsheet parameters that would normally be changed by the user are marked in BOLD RED fonts. The simulation spreadsheet can be found at www.windowoutdoors.com.

Table 2.2: Constant Parameters of a Watershed for the Bioretention Sizing Simulation.

Total Watershed Area, acre	0.03
Pre-Development Curve Number (CN) (Desert shrub - poor)	77.0
Pre- Development S= (1000/CN) -10	2.99
Pre-Development Initial abstraction - in Ia=0.2S	0.60
Impermeable Portion in Watershed Area (SE roof) , sq ft	410
Post-Development CN of the Impermeable Areas	98.0
Lawn Portion in Watershed Area ,sq ft	806
Post-Development CN of the Lawn Areas	96.0
Combined Post-Development CN	97.0
Post-Development S= (1000/CN) -10	0.34
Post-Development Initial abstraction, in Ia=0.2S	0.07
Bioretention Unit Depth, ft	1.00
Bioretention Unit Backfill Porosity, %	30.0

For each day in this spreadsheet, the date and the precipitation were inserted at the first cells. In the next column, the pre-development net precipitation, which corresponds to the precipitation after losses to the initial abstraction (I_a) that can be calculated using equation (2.2). After that, the pre-development runoff is calculated in inches using equation (2.1) and then it is converted to volume (acre-in) by multiplying it with the total watershed area. Then, the same calculations were conducted for the post-development conditions. The last column contained the difference between the volume of the bioretention unit and the post-development runoff. These calculations were applied for every single day for twenty years of historical data collected at each of the three study cities.

Table 2.3: Variable Parameters of a Watershed for the Bioretention Sizing Simulation.

year	Day	P, in	Pre_P-Ia, in	Pre-D R, in	Pre-D R, acre-in	Post_P-Ia, in	post-D R, in	Post-D R, acre-in	Post-D R After Capture, acre-in
1991	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1991	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
.	.	.	.	.	.	.	.	.	.
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.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
2010	7302	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	7303	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	7304	0.08	0.00	0.00	0.00	0.01	0.00	0.00	0.00
2010	7305	0.16	0.00	0.00	0.00	0.09	0.02	0.00	0.00
				Sum	0.24			Sum	0.24

The spreadsheet uses the input watershed and deign parameters to estimate the total 20 year runoff from the pre-development watershed and the developed watershed. The user of the spreadsheet must iterate on (successively guess) the area and depth of the bioretention cells that will cause the pre and post development runoff to be identical.

Table 2.4: The Differential Equation of the Bioretention Sizing Simulation.

Total Bioretention Unit Surface Area, sq ft	286
Total Bioretention Unit Storage Volume, cubic ft. equation (2.7)	85.8
Differential equation: (Pre- development runoff – Captured post development runoff)	0.00

2.5 Vegetation

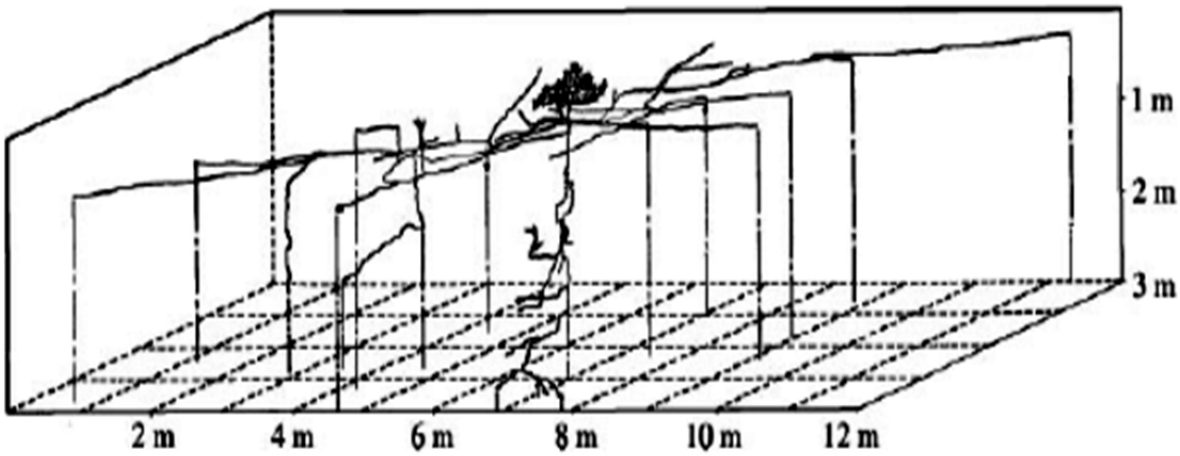
A passive design is one that uses the soil rather than a tank to store water. In this study, the design aims to eliminate the need to irrigate the landscape plants. Unless a long drought period (>20 years drought) is encountered, plants will be watered by the infiltrating runoff water that is captured by the bioretention units and stored in the soil therein. This strategy fits with trees and shrubs that are native to the Southwest region because they have a high drought resistance, a deep root system, and low water consumption.

The designed landscape for this study is completely passive; therefore, grasses and high water consuming plants are excluded. Since the design is generalized to three cities in the region including El Paso, Albuquerque, and Phoenix, the shrubs and trees are carefully selected to be native for all of the cities. The selected shrubs and trees, shown in table (2.2), have low water requirements. In addition, they have wide and deep root systems, which allow them to reach the water stored in the soil away from them. Therefore, they can be grown not only in the bioretention units but also in the area around them.

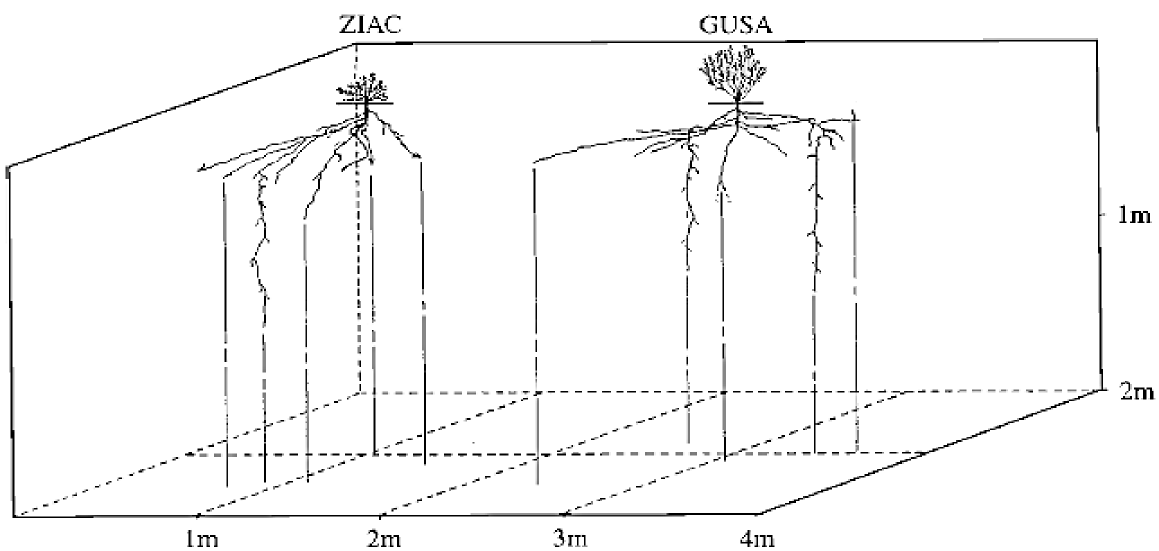
Table 2.5: Selected Shrubs and Trees for the Passive Landscape Design. (The City of El Paso Tree Board, 2004)

Scientific Name	Common Name	Type	Height Ft	Width Ft	Evergreen Or Deciduous	Water Requirements
Ceratoides Lanata	Winterfat	Shrub	3	2	Evergreen	Low
Larrea Tridentata	Creosote Bush	Shrub	8	6	Evergreen	Low
Koberlinia Spinosa	Crucifixion Thorn	Shrub	5	7	Evergreen	Low
Atriplex Canescens	Four Wing Saltbush	Shrub	6	8	Simi-Evergreen	Low
Leucophyllum Frutescens	Texas Sage/Ranger	Shrub	4-8	4-8	Evergreen	Low
Acacia Berlandiera	Guajillo	Shrub	12	12	Deciduous	Low
Prosopis Glandulosa	Honey Mesquite	Tree	30	30	Deciduous	Low
Chiloposo Linearis	Desert Willow	Tree	25	20	Deciduous	Low
Fraxinus greggii	Gregg's Ash	Tree	15	8	Semi-Evergreen	Low
Quercus Arizonica	Arizona White Oak	Tree	35	30	Evergreen	Low

P.G. Robert and M.L. Lenz conducted a study in 2000 about the root systems of some Chihuahuan Desert plants. They found that most of shrubs have root system depth of 2 meters (6.5 ft) or more, while trees have a deeper root system up to 3 meters (10 ft). Also they found out that tree root systems are wider than shrub roots (figure 2.11)



a. Root System of a Honey Mesquite.



b. Root System Desert Zinnia (ZIAC) and Snakweed (GUSA).

Figure 2.11: Root System for Some Chihuahuan Desert Plants. (Robert and Lenz, 2000)

2.6 Passive Rainwater Landscape Design.

After determining the size of the bioretention cells and the landscape vegetation, water balance between the water stored in the soil at these cells and the other hydrologic parameters including precipitation, evapotranspiration, and runoff will be conducted. The subject of the

simulation is to determine the supportable crown green area of high drought tolerant shrubs and trees that can be watered by the water captured and stored in the soil at the designed LID facility after the roots are completely established. The same watersheds' subdivision that was used for the LID design is used here. Twenty years of historical participation and temperature data is used for the passive landscape design. The crown green area will be calculated for every watershed based on its features and properties.

The general balance equation that is used for the simulation is:

$$\Delta S = P + R - ET \tag{2.8}$$

Where:

ΔS = Change in the volume of available water storage in the soil (cu ft).

P= Precipitation (cu ft).

R= Runoff (cu ft).

ET= Evapotranspiration (cu ft).

2.6.1 Water Storage:

Water storage that is included in this design is the water retained in soil at the area of the bioretention units, and that is available for plants. The plant available water is the unbound water held in soil and available to the plant for uptake. This water falls into the range between two soil water contents (figure 2.12): the dry end (wilting point) and the moist end (field capacity). Field capacity is the percentage of the water content (Θ) remaining in the soil after 48-72 hours of a gravitational drainage when the soil has been saturated by a significant irrigation or precipitation events. The drain time differs from soil type to another depending on the drainage rates.

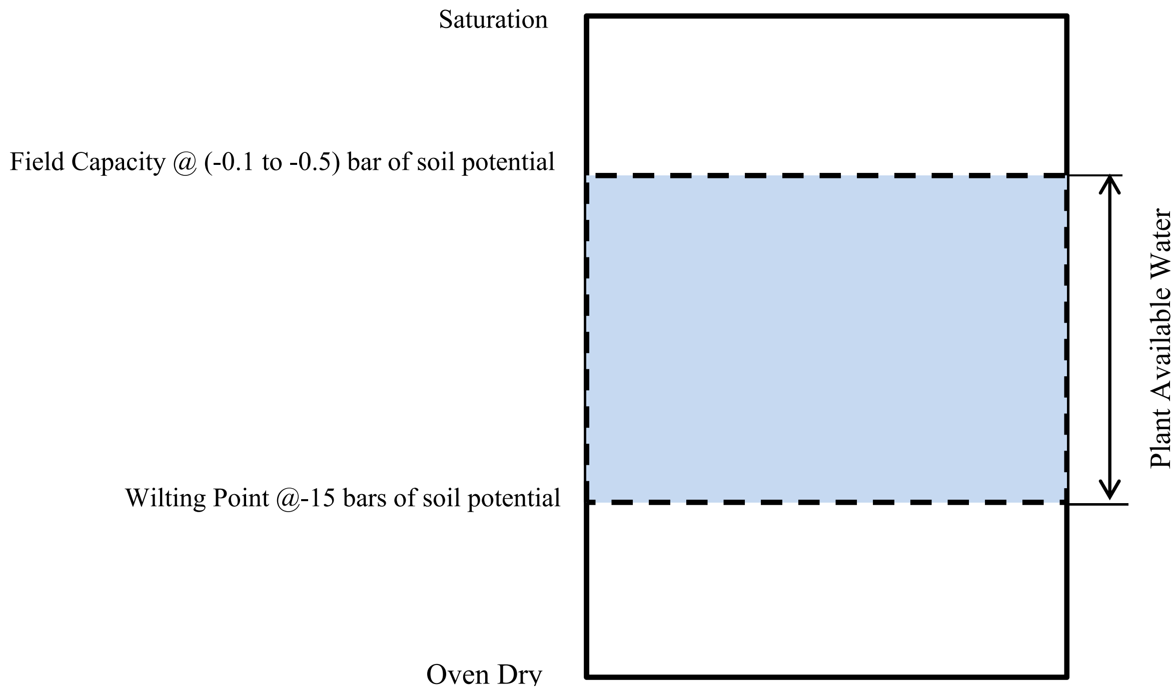


Figure 2.12: Soil Water Content.

The wilting point is the water content in the soil at which the plant reaches the wilting condition. The wilting point also differs based on soil texture (figure 2.13). According to David S. B. and Judith L. S. (1999), soil water content at field capacity corresponds to matric potentials in the range of -0.10 to -0.5 bar depending on the soil texture, while soil water content at the wilting point is reached in most soils when value of the msatric potential of -15 bars.

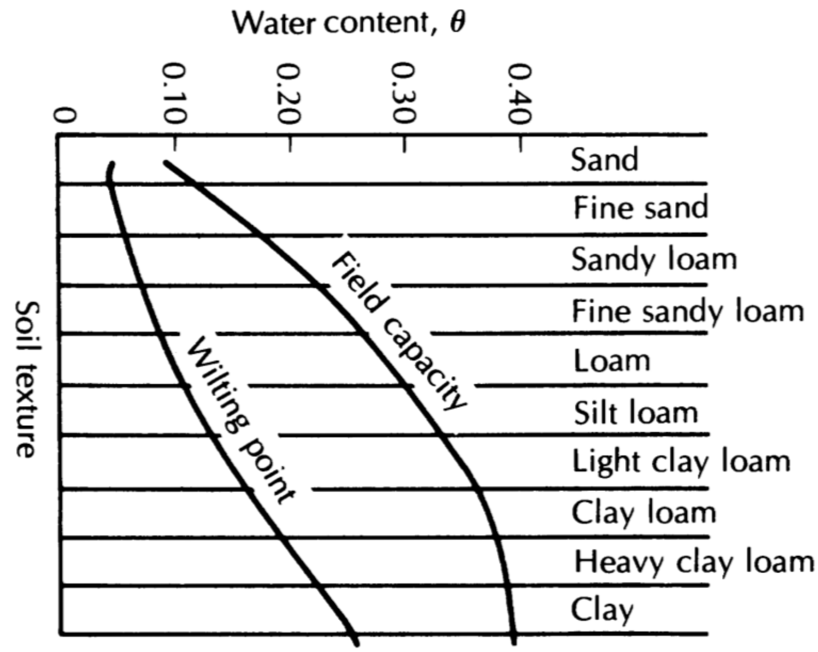


Figure 2.13: Soil Water Content Based on Texture. (U.S Department of Agriculture, yearbook 1955).

The soil texture for this study is assumed to be deep loam soil; this soil has a wide range of plant available water as shown in figure (2.14) described by Brady, N. C. and. Weil, R. R. in 1999. The values of water content (Θ) at the field capacity and the wilting point shown in the figure are used in this study were Θ= 0.38 and 0.08 at the field capacity and the wilting point respectively.

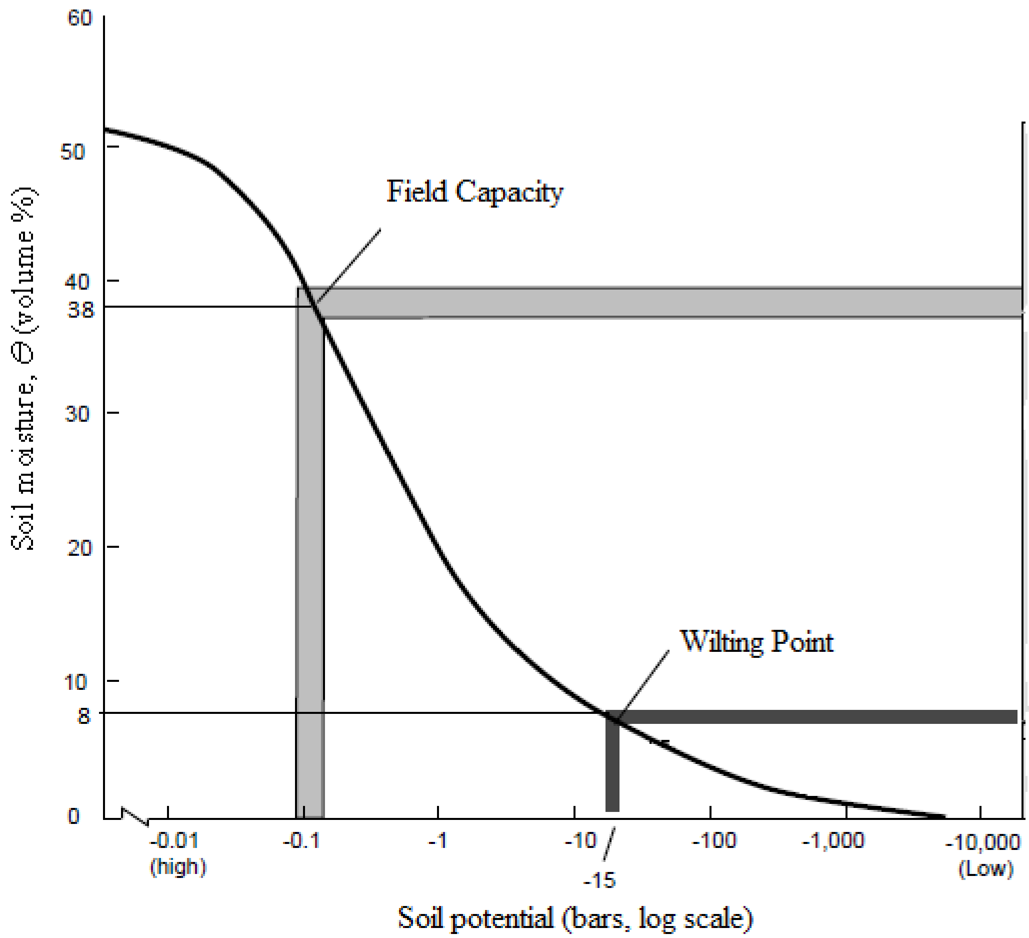


Figure 2.14: Water Content (Θ) at the Field Capacity and the Wilting Point for Loam Soil. (Brady and Weil, 1999).

The boundaries of water storage volume are shown in figure (2.15). Usually, the section of the infiltrating water is narrow at the surface and then it scatters gradually when the water soaks deeper. However, the assumption for the water section is to add 1foot to each side of the bioretention units. The lower boundary is determined by the root depth, which differs between shrubs and trees with 5 ft for shrubs and 10 feet for trees. The root depth is averaged when the vegetation area has both shrubs and trees (Table 2.4)

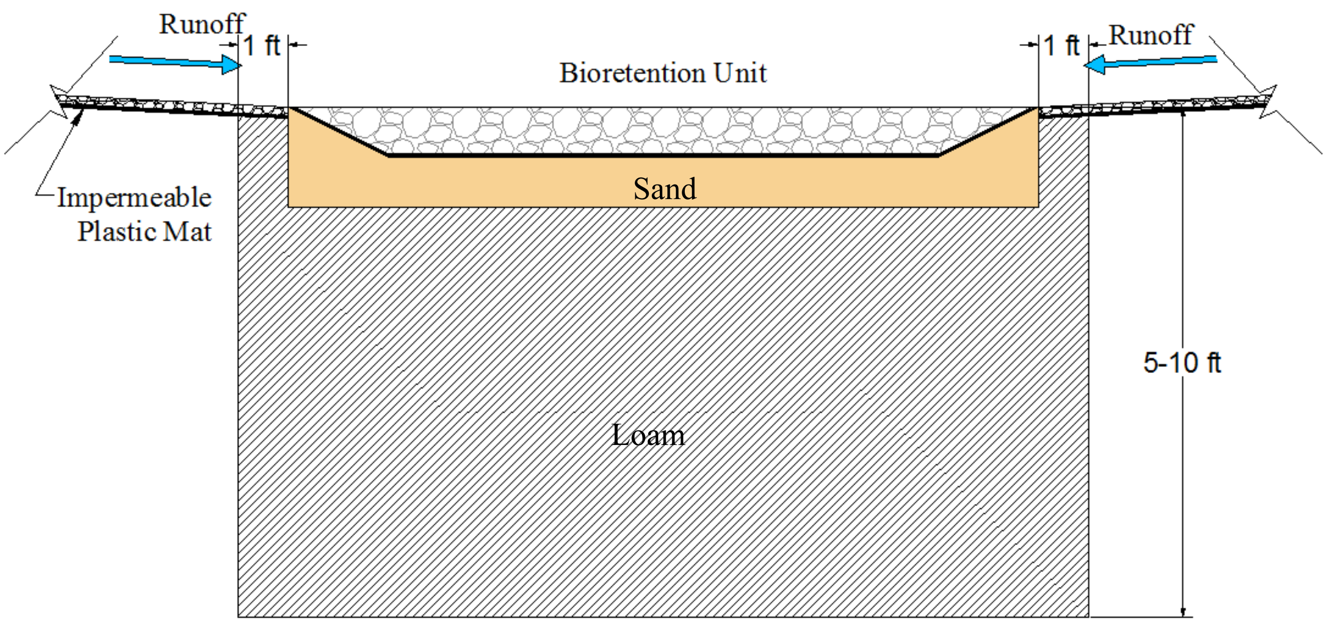


Figure 2.15: The Water Storage Boundaries.

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The volume of water storage can be calculated using this formula:

$$V_s = \Theta * ((L+1) * (B+1)) * D \quad (2.9)$$

Where:

V_s = Volume of water storage (cu ft).

Ɵ = Volumetric water content (%).

L = The bioretention unit length (ft).

B = The bioretention unit width (ft).

D= The average depth of vegetation root (ft).

2.6.2 Evapotranspiration

Evapotranspiration (ET) corresponds to the loss of water to the atmosphere from the soil both by evaporation from the soil surface and by transpiration from the plants growing thereon (figure 2.16).

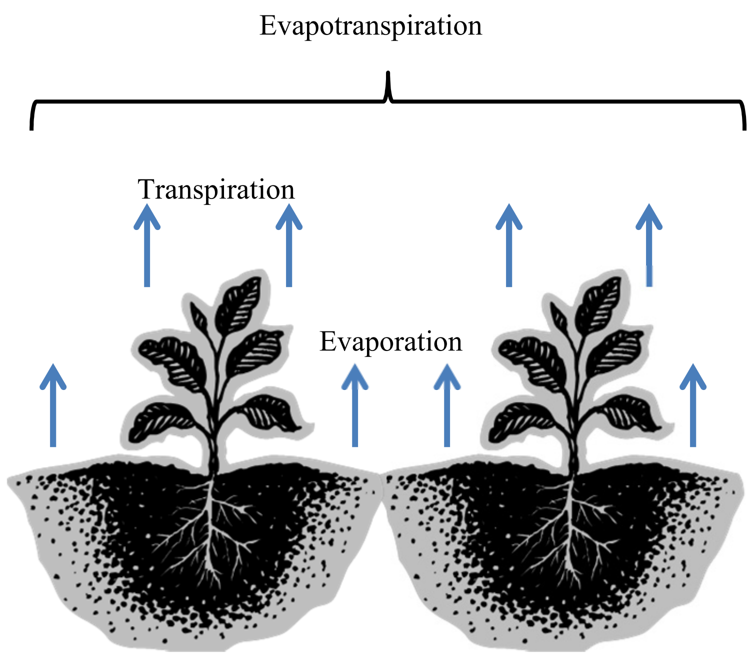

Figure 2.16: Evapotranspiration Method.

Evapotranspiration is a complicated parameter in the water balance because it is affected by many factors such as temperature, relative humidity, solar radiation, and wind speed. Many methods have been used to estimate the evapotranspiration rate. Mostly, empirical equations, such as Penman, Priestley-Taylor, Thornthwaite, or Blaney-Criddle, are used to estimate the potential evapotranspiration rate (ET). These equations calculate ET using inexpensive and available weather data assuming that plants are fully irrigated. B. Woodhouse (2007) provides

ET rates for various types of vegetation across Southwest. She collected the data from different federal and state agencies and universities. According to Woodhouse, these rates (Table 2.3) were obtained by using direct and empirical methods.

Table 2.6: ET Rates for Various Natural Vegetation Types Across the Southwest. (Woodhouse, 2007)

Vegetation	Location	ET rate (inches/year)
Salt cedar	Gila River, AZ	56
Salt cedar	Middle Rio Grande, NM	42-57
Salt cedar	Middle Rio Grande, NM	34-49
Salt cedar	Colorado River near Blythe, AZ	28-30
Cottonwood	Middle Rio Grande, NM	65-85
Cottonwood	Middle Rio Grande, NM	44-53
Cottonwood	San Pedro River, AZ	19-28
Mesquite	San Pedro River, AZ	27
Mesquite	San Pedro River, AZ	25-26
Honey mesquite	Colorado River near Blythe, AZ	19
Russian olive	Middle Rio Grande, NM	42-50
Ponderosa pine	Northern AZ, high elevation	20
Ponderosa pine	Nevada and northern NM	11--19
Pinyon-juniper	Northern AZ, mid-elevation	16
Pinyon-juniper	Nevada	12
Grass	Middle Rio Grande, NM	2.8-23
Shrub	Middle Rio Grande, NM	0-14
Mixed; low elevation	Middle Rio Grande, NM	0-16
Xerophytes	Nevada	9-12
Sagebrush	Nevada	12
Sage and bitterbrush	Nevada	10-18

The ET rates that illustrated in the previous table are used for this study. However, because the rates are given in units of inches per year, and the simulation requires the rates to be inches per day, a reasonable conversion was used for this purpose. Because of the direct correlation between the temperature and the evapotranspiration, the ET rate was distributed among the days based on the measurements of temperature in these days meaning that the day would have an ET rate that is corresponding to its temperature. At a temperature of 32 ^{o}F or less

ET is assumed to be zero (Willmott, C. J et al, 1985). The evapotranspiration (ET) in inches per day was calculated using the following equation.

$$(\mathrm{ET})_i\left(\frac{\mathrm{in}}{\mathrm{day}}\right) = \frac{\mathrm{T_i}}{\sum_{\mathrm{i=n}}^{\mathrm{i=1}} \mathrm{T}} * \left(\mathrm{ET}\,\frac{\mathrm{in}}{\mathrm{year}} * \mathrm{N}\right) \qquad (2.10)$$

Where:

T = temperature > 32 ^{o}F.

i = day rank.

n = number of daily temperature data.

N= number yearly data.

The vegetated area includes shrubs and trees in most of the cases. Areas covered with shrubs have a lower evapotranspiration rate than the areas covered with trees do. For this study, five different percentages of shrubs and trees in the vegetation crown area were calculated. These percentages are: 0%, 25%, 50%, 75%, and 100%.Therefore, the evapotranspiration rate of the vegetation area was averaged using this equation:

$$\text{Ave ET} = \left(\frac{\mathrm{A_{sh}}}{\mathrm{A_T}} * \mathrm{ET_{sh}}\right) + \left(\frac{\mathrm{A_{tr}}}{\mathrm{A_T}} * \mathrm{ET_{tr}}\right) \qquad (2.12)$$

Where

A_{sh} = crown area of shrubs.

ET_{sh} = Evapotranspiration rate for shrubs (in/day).

A_{tr} = crown area of trees.

ET_{tr} = Evapotranspiration rate for trees (in/day).

T_T = Total area (summation of the area of shrubs and the area of trees).

The values of the evapotranspiration rates that were used for the landscape simulation is:

Table 2.7: Averaged ET Values Based on Vegetation Area Subdivision and Averaged Root depth.

Vegetation area subdivision	ET (in/year)	Depth of root system (ft)
100 % trees 0% shrubs	25	10
75% trees and 25% shrubs	21	8
50% trees and 50% shrubs	16	7
25 % trees and 75% shrubs	12	6
0 % trees and 100% shrubs	7	5

After calculating the daily ET (inches/day) the volume of water loss by the evapotranspiration is:

$$ET\ (\text{cubic feet}) = A_c\ (\text{sq ft}) * \text{Ave } ET\ (\text{ft}) \quad (2.11)$$

Where:

A_c = vegetation crown area.

2.6.3 Precipitation

The volume of the precipitation water that is involved in the water balance includes only the direct participation over the bioretention unit area. This volume can be calculated using the following equation:

$$P\ (\text{cu ft}) = P\ (\text{ft}) * A_s \quad (2.12)$$

Where:

A_s = Bioretention surface area (sq ft).

2.6.4 Runoff

The volume of the runoff that included in the water balance is the whole runoff amount generated in the watershed because it is directed and conveyed to the bioretention cell. However, the maximum runoff volume can be taken in consideration in this simulation is equal to the capacity of the bioretention unit. Any excessive amount will be transmitted to the following unit or to the street from the system outlet. The volume can be calculated using the same method that used when calculating the bioretention size.

2.6.5 Simulation of the Landscape Design.

Another simulation was developed to calculate the crown vegetation area that can be passively grown when the root have completely established. The simulation was prepared where the parameters can be easily adapted to any watershed condition and to any vegetation properties. An adjacent table (Table 2.8) was prepared to contain the simulation's constant parameters including: vegetation evapotranspiration rate (in/year), soil field capacity and wilting point, watershed curve number (CN) and initial abstraction (in), the bioretention unit area and the storage size, and the soil storage depth (root depth). These parameters can be simply changed based on the properties of each water shed and based on how much tree/shrub ratio is desired to be grown. In the spreadsheet parameters that would normally be changed by the user are marked in BOLD RED fonts. The simulation spreadsheet can be found at www.windowoutdoors.com.

Table 2.8: Parameters of a Watershed for the Landscape Simulation.

Evapotranspiration Rate (ET), in/day	0.04
Existing Soil Field Capacity %	38
Existing Soil Wilting Point %	8.0
Capture Area Curve Number (CN)	97
S= (1000/CN) -10, in	0.31
Initial Abstraction, in Ia=0.2S	0.06
Bioretention Unit Surface Area, sq ft	286
Soil Storage Surface Area, sq ft	357
Total Capture Area, sq ft	1217
Bioretention Unit Depth, ft	1
Bioretention Unit Backfill Porosity, %	30
Bioretention Unit Volume, cu ft	85.8
Root Depth, ft	7
Vegetation Crown area, sq ft	620

For each day throughout the twenty years, the following calculations were conducted (Table 2.9):

- The net precipitation (P-Ia).
- The runoff using equation 2.1.
- The daily evapotranspiration rate based on the temperature where the any day with temperature less than 32 had zero evapotranspiration and the evapotranspiration rat was calculated using equation 2.10.
- The Water storage where the soil assumed to be watered before first day and reached the field capacity at the entire storage size, so the storage volume at the first day equalled to the soil field capacity multiplied by the storage volume. After that, for the following days

the storage volume equal to the minimum value between the storage volume ate the soil filed capacity or the maximum value between the storage volume at the wilting point or the existing water volume plus the direct precipitation over the bioretention unit plus the minimum value between the runoff generated in the watershed and the bioretention unit volume minus the evapotranspiration rate multiplied by the vegetation crown area.

Table 2.9: Variable Parameters for the Landscape Simulation.

Year	Day	P, (in)	Net P, in	R, in	T, °F	T>32, °F	ET Daily portion	ET, in	Water Storage, cub ft	Water Storage, in
1991	1	0.00	0.00	0.00	44.1	44.1	9.19E-05	0.03	1478.0	31.9
1991	2	0.00	0.00	0.00	42.1	42.1	8.78E-05	0.03	1477.0	31.9
1991	3	0.00	0.00	0.00	43.5	43.5	9.08E-05	0.03	1475.0	31.9
1991	4	0.00	0.00	0.00	45.0	45.0	9.38E-05	0.03	1474.0	31.8
1991	5	0.00	0.00	0.00	46.0	46.0	9.60E-05	0.03	1472.0	31.8
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2010	7301	0.00	0.00	0.00	45.9	45.9	9.57E-05	0.0306	1303	28.1
2010	7302	0.00	0.00	0.00	51.3	51.3	1.07E-04	0.0342	1301	28.1
2010	7303	0.00	0.00	0.00	50.7	50.7	1.06E-04	0.0339	1300	28.1
2010	7304	0.08	0.02	0.00	52.5	52.5	1.10E-04	0.0351	1298	28.0
2010	7305	0.16	0.10	0.06	34.9	34.9	7.28E-05	0.0233	1300	28.1

The change in the water storage in the soil was plotted for the all days in the twenty years and the vegetation crown area was iterated (adjusted by trial and error) to have a reasonable value that water storage content did not drop under the wilting so the plants would die or no large amount of water would be lost. The following plots of shows different cases of the change in water storage with different vegetation crown area:

- The first plot (Figure 2.17) shows the case where the vegetation crown area is larger than the size that can be passively fed by the water stored in the soil, so the plants in this case need to be watered at the drought period.

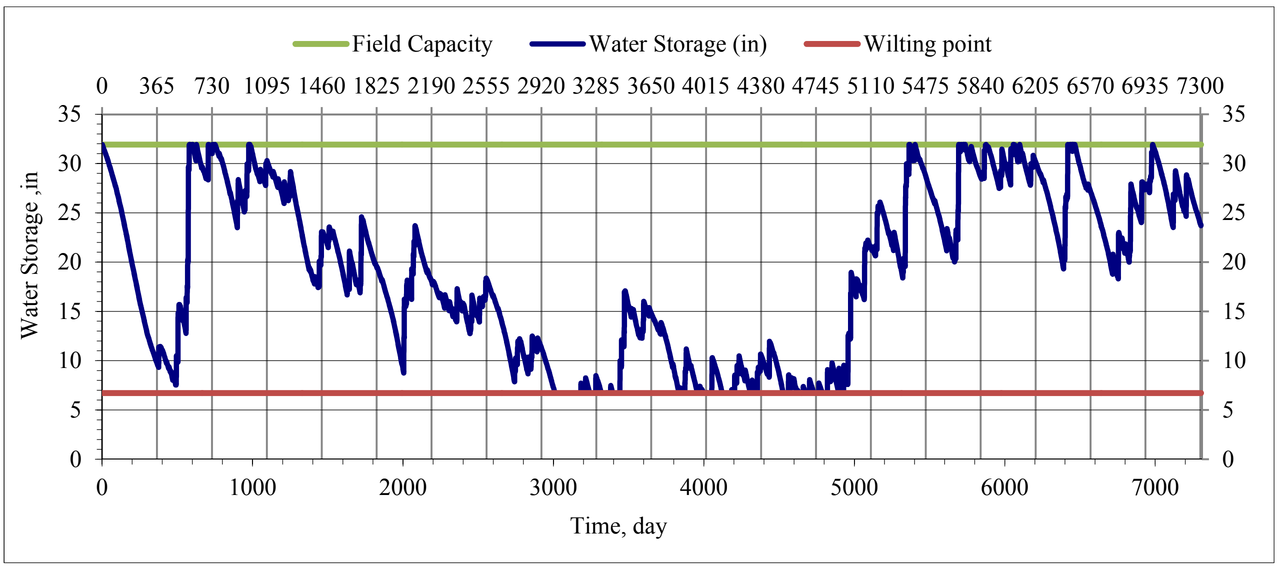


Figure 2.17: Change in Water Storage of Large Passive Vegetation Crown Area.

- The second plot (Figure 2.18) shows the case where the vegetation crown area is small, so most of the stored water would not be used by the plants and would be lost to deep infiltration or evaporation.

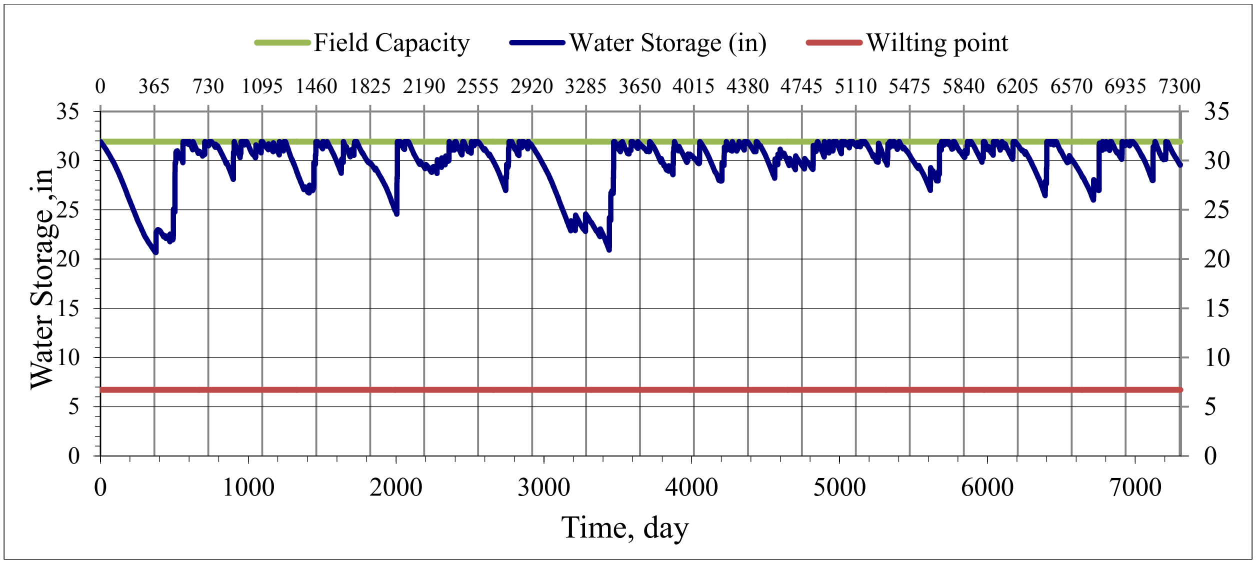


Figure 2.18: Change in Water Storage of a Small Passive Vegetation Crown Area.

- The third plot (Figure 2.19) shows the case where a moderate vegetation crown area is grown where it can be passively fed by the water stored in the soil without watering and with small water loss. This value can be obtained after several iterations.

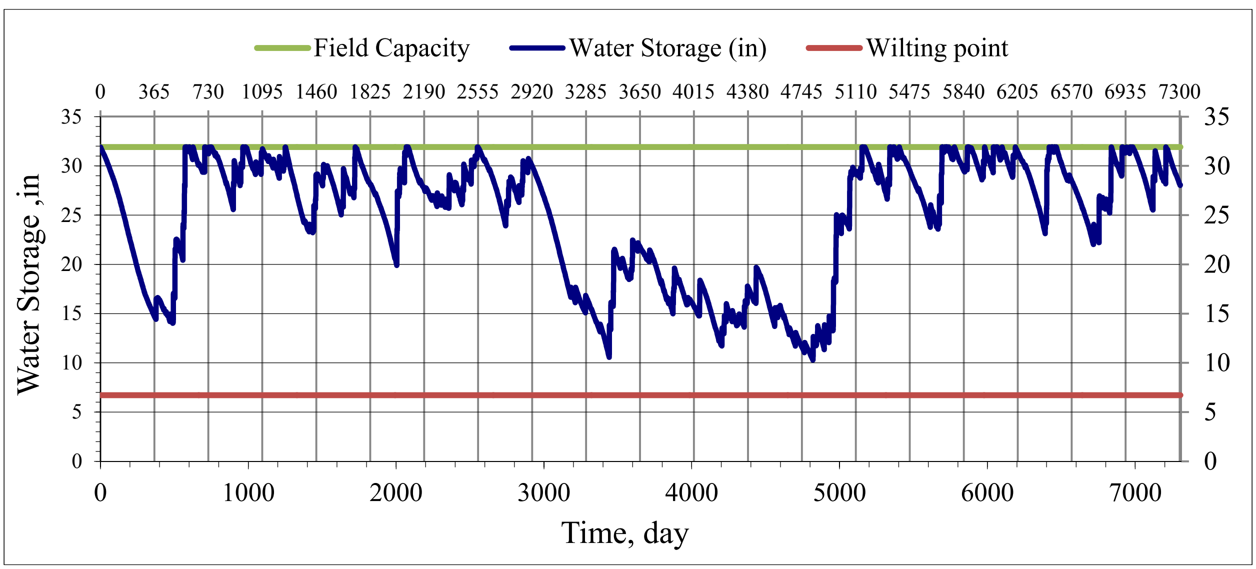


Figure 2.19: Change in Water Storage of a Moderate Passive Vegetation Crown Area.

2.7 Statistical Analysis for Historical Temperature and Precipitation Data

The statistical analysis for the daily historical precipitation and temperature data is a necessary step for the design. This step gives a general conception about the data. For examples, knowing the maximum precipitation helps in determination of the type of overflow drain system. The following table presents a summary to the statistical analysis for El Paso, Albuquerque, and Phoenix. Table (2.5) includes the annual analysis of 20 years of the temperature and the precipitation data from 1991 t0 2010. The data was downloaded from this website: (http://www.tutiempo.net/en/). In addition, the table contains the net precipitation.

Table 2.10: Annual Statistical Analysis of 20 Years Historical Precipitation and Temperature Data for El Paso, Albuquerque, and Phoenix.

Analysis category	El Paso			Albuquerque			Phoenix		
	Precipit-ation, in	Net Precipita-tion, in	Temper-ature, °F	Precip-itation, in	Net Precipita-tion, in	Temper-ature, °F	Precipitati-on, in	Net Precipita-tion, in	Temperatu-re, °F
Mean	8.96	6.63	65.7	9.63	6.67	57.7	8.31	6.47	75.1
Std. Error of Mean	1.16	1.02	0.18	0.68	0.56	0.19	1.32	1.18	0.18
Median	8.47	5.72	67.5	9.81	7.19	58.3	7.62	5.41	75.0
Mode	0.00	0.00	78.1	10.02	0.18	73.9	0.00	0.00	92.8
Std. Deviation	5.20	4.55	15.2	3.03	2.51	16.1	5.88	5.26	15.7
Variance	27.1	20.8	232	9.16	6.29	260	34.61	27.6	245
Skewness	1.09	1.46	-0.23	-1.40	-0.82	-0.12	1.85	2.08	-0.04
Std. Error of Skewness	0.51	0.51	0.03	0.51	0.51	0.03	0.51	0.51	0.03
Kurtosis	2.53	2.90	-1.07	3.28	0.80	-1.18	4.86	5.73	-1.30
Std. Error of Kurtosis	0.99	0.99	0.06	0.99	0.99	0.06	0.99	0.99	0.05
Range	23.54	19.7	76.8	12.8	10.3	77.5	27.1	23.8	73.8
Minimum	0.00	0.00	22.3	0.50	0.18	14.4	0.00	0.00	32.0
Maximu m	23.5	19.7	99.1	13.3	10.5	91.9	27.1	23.8	106
Number of days when P>0			54.0		69.0			40.0	
Number of days when Net P>0			26.0		31.0			22.0	

The distribution of the average monthly precipitation and the net precipitation after the loss to initial abstraction between 1999 and 2010 for the three representative cities are shown in the following figures.

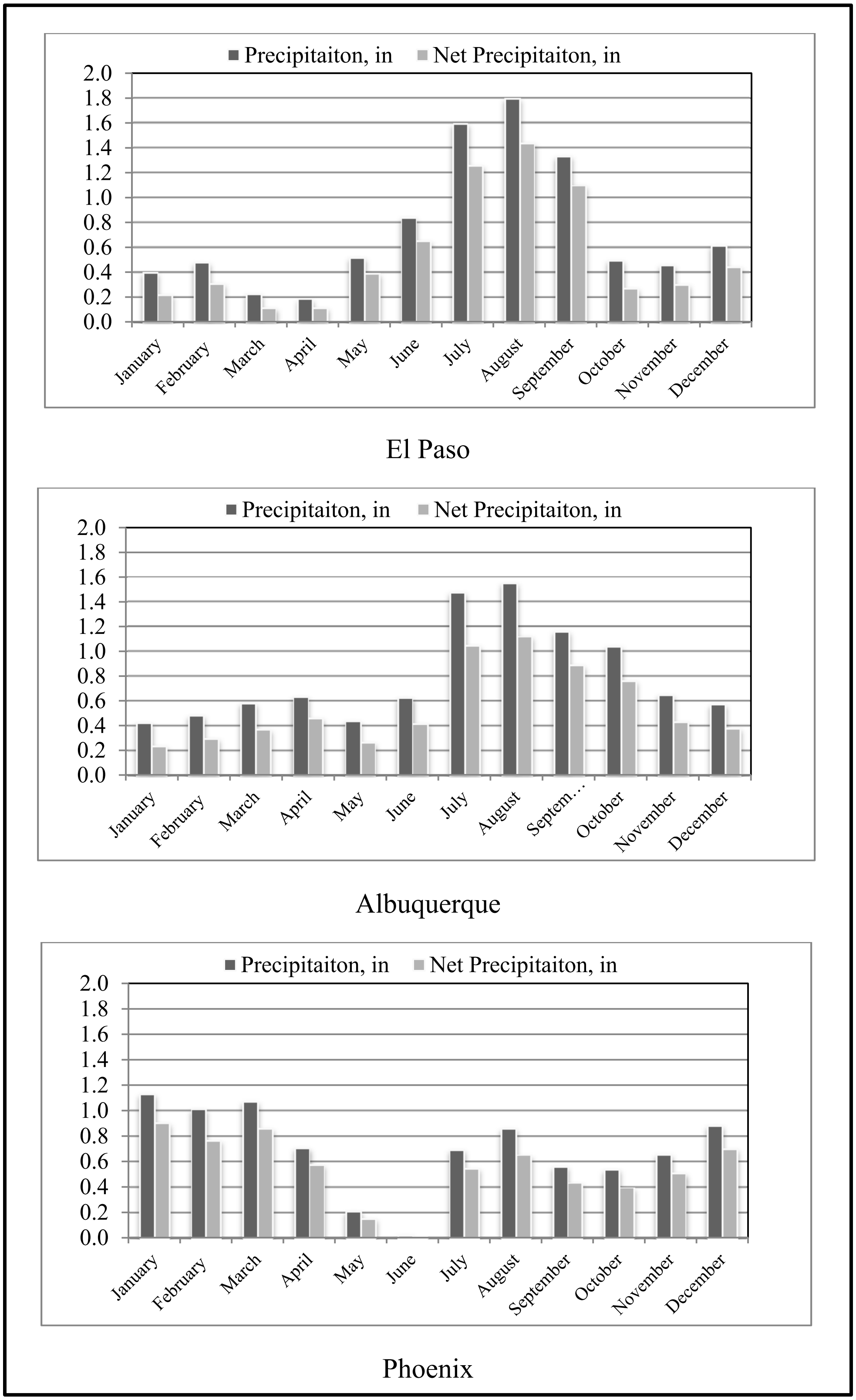


Figure 2.20: Mean Monthly Precipitation and Net Precipitation from 1991 -2010 for El Paso, Albuquerque, and Phoenix.

2.8 Landscape Differential Cost

This step is to compare the cost of the conventional landscape and the cost of the passive landscape that is designed in this study. This passive landscape consists of native shrubs and trees, which have low water requirements. These requirements are fulfilled by the water stored in designed bioretention units once the plants' roots established. The conversion from a conventional landscape, where municipal water is used for landscape irrigating, to a passive landscape results in considerable savings of water thus budget.

In this section, the cost of the initial, 3 year, 6 year, 10 year, and average annual costs for the conventional landscape and the passive landscape are compared for the three studied cities. The comparison categories includes: the initial landscape cost, the water cost due to irrigation, vegetation maintenance, and the yard waste disposal cost. The cost estimation is conducted using a cost calculator tool provided by the Environmental Protection Agency (EPA). The calculate tool is designed to calculate the low and the high cost estimate of converting a conventional landscape to a passive one. The EPA calculator provides various rates collected from many sources for the all cost categories. In addition, it has an inflation adjustment feature that allows users to adjust the currency value to the year needed.

In order to estimate a landscape cost using the calculator tool, the landscape area has to be divided to three zones: a regular watering zone, an occasional watering zone, and a natural rainfall (or zero watering) zone. The difference between the first two zones is that in absence of rain plants in the regular watering zone need watering once every week or more once established. On the other hand, the plants in occasional watering zone require watering once every two or three weeks. The calculator defines the regular watering zone as an area that is watered four to

eight times per month during the growing season; the occasional watering zone is an area watered between one and three times per month during the growing season; and the natural rainfall zone is an area that is never watered. The regular water regular zone usually planted with grasses and flowers, which have high water requirement while the plants in occasional watering zone usually have lower water requirements, and the lowest water requirements plants are in the natural watering zone. The calculator requires determining the length of the growing season in your region, which can be found in this map:

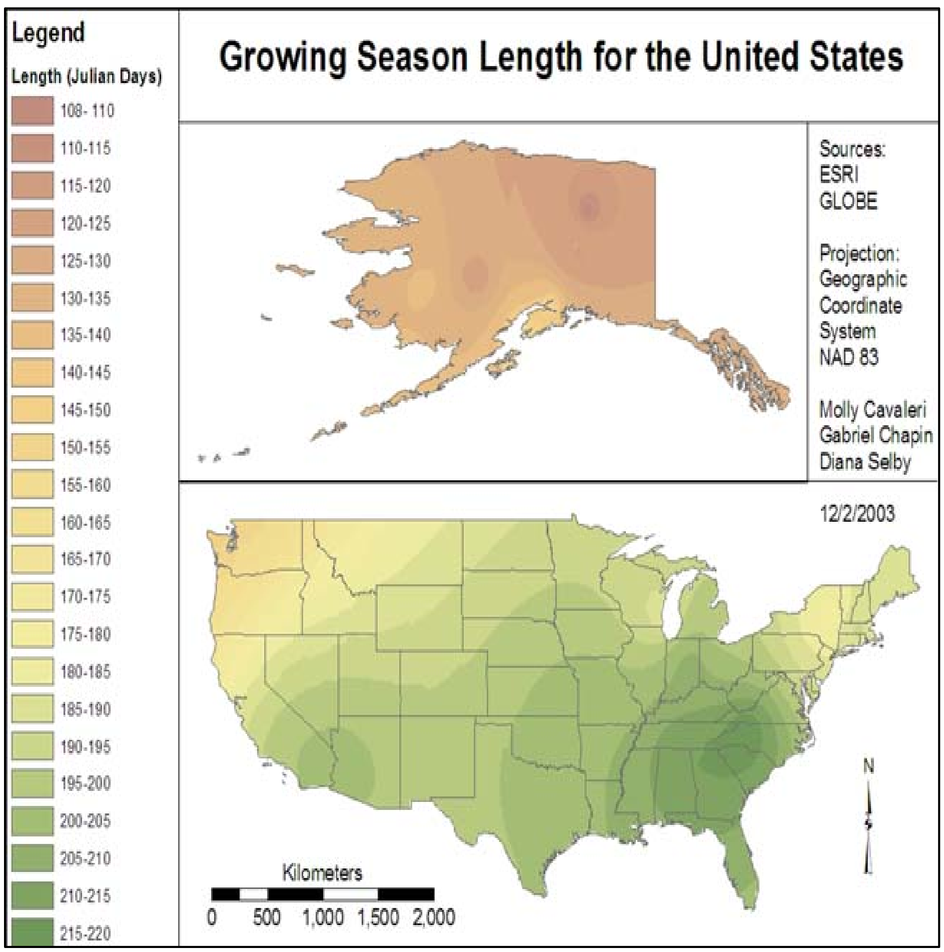


Figure 2.21: Growing Season Length for the United States.
(http://warnercnr.colostate.edu/avprojects/globe/phenology/images/layout_growing.jpg)

In order to compare between the two landscape types, a same area size assumed to be planted. The area of the landscape assumed to be 50% of the total residential lot area. For the

conventional landscape, 20% of the landscape is in the regular watering zone, and half of this zone is turf and the other half is flowers. The rest of the landscape area is in the occasional watering zone, and includes trees and shrubs that need to be watered between one and three times per month. For the passive landscape, all the plants are in the natural watering zone, which is divided equally between trees and shrubs. The initial landscape cost is assumed to be the same for both types. The water rates are taken from the water utility official website of every city. The rates (table 2.6) are calculated based on the number of irrigations required per month and the amount of water needed per irrigation.

Table 2.11: Landscape Water Rate for the Three Cities of the Study.

City	Water rate, $/1000 gallon	Source
El Paso	4.5	http://www.epwu.org/services/water_rates.html
Albuquerque	1.1	http://www.abcwua.org/content/view/220/408/
Phoenix	3.6	http://phoenix.gov/waterservices/customerservices/payment/rates/index.html

3. Soil Moisture Sampling

3.1 Background

The total volume of a soil consists of about 50% pore space and 50% solid matter (Brady and Weil, 1999). Water infiltrating into the soil surface fills the pore spaces completely. The water continues to soak down into the sub layer of the soil replacing air as it moves. When the soil pores are full of water, it is said to be saturated. After the water source stops, the water drains out of the pores, and the soil becomes unsaturated. Water in the soil below the saturation level in the soil is retained against gravity. The forces that hold the water in the soil result from cohesion of water molecules to each other and adhesion of water molecules to soil grains' surfaces.

The movement of soil water is an energy-related process (Brady and Weil, 1999). Water, likewise any other materials, has a tendency to move or change from a state of higher energy to a state of lower energy. For example, in soils, water will move from an area where the free energy of the water is high, which is a wet soil, to an area where its free energy is lower, or to a dry soil. The differences in energy levels in a soil profile determine the direction of water movement.

Soil water content is defined as either the weight of water per unit weight of dry soil or as the volume of water per unit bulk volume of soil. It can be determined at saturation or at any degree of unsaturation. On the other hand, the soil suction (soil potential) is defined as the difference between the free energy of soil water and that of the water at pure state. The soil potential is measured in tension units and expresses the tightness of the forces that are applied upon the water by the soil particles.

3.3 Study Area

In this study, the water content and the soil suction were measured for 10 months at five stations placed at two different locations with different conditions (Figure 3.1). The first location should have been the model house whose Integrated Management Practices (IMP) system and passive landscape were designed in this study. However, the limited fund stood against the implementation of the system; therefore, another location, which is a single family residence that already has a simple Low Impact Practices and landscape, was selected for this study. It is located at Turney Drive, El Paso, TX (Latitude: 31^{o} $47^{'}$ $16.73^{''}$N, Longitude: 106^{o} $30^{'}$ $2.15^{''}$W). Three of the five stations were installed in here and labelled as A1, A2, and A3. The second location, where the other two stations (B1 and B2) were installed, is at a desert location by El Paso about 15 miles toward the northwest from the first location. Its coordinates are: Latitude: 31^{o} $48^{'}$ $40.40^{''}$N, Longitude: 106^{o} $36^{'}$ $5.41^{''}$W. The purpose of selecting these different locations is to compare the differences in the process of energy change between an urban location, where the soil has been disturbed the surface is changed, and in a standard place.

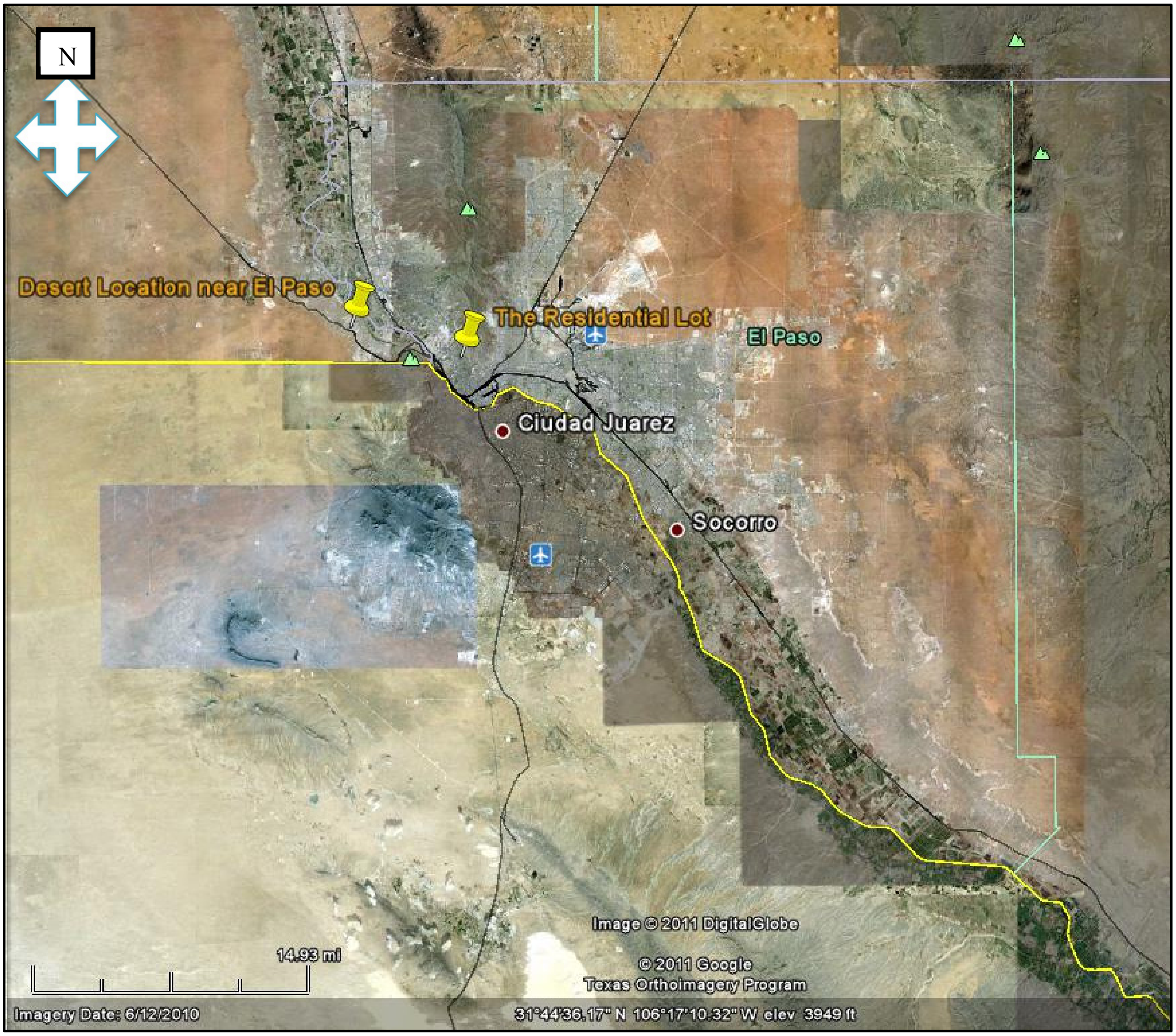


Figure 3.1: The Location of Soil Moisture Measurement Stations.

3.3 Measurement Tools

Before installing the sampling station, two portable devices of soil moisture measurement were examined and tried: 1) Time Domain Reflectrometry (TDR), and 2) Tensiometer Probe.

3.3.1 Soil Water Content Measurement (TDR)

Time Domain Reflectrometry (TDR) is designed to allow users determine the volumetric water content (VWC %) in soil easily and quickly, and take as many measurements as wanted in the field. It consists of two connected parts: a probe and a digital meter, shown in figure (3.2).

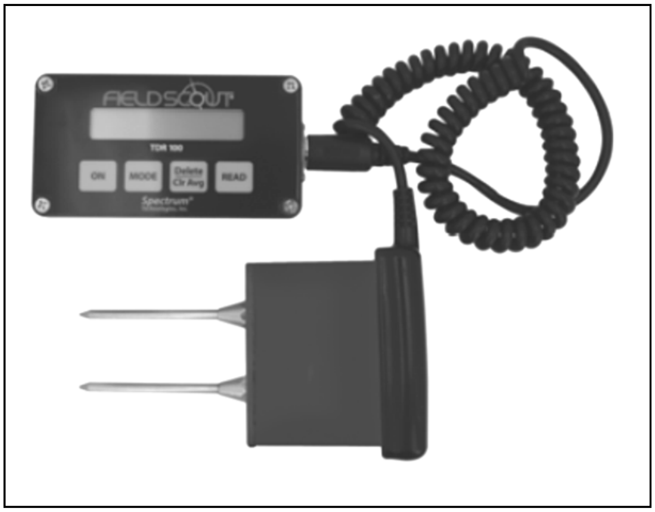


Figure 3.2: TDR

TDR comes with four different rod lengths which can be easily changed based on the desired depth. The length has been experienced and used for this study is the tallest provided one, which is 7.9 inches rod. TDR sends a high- frequency electromagnetic wave along the cable attached to the two parallel stainless rods inserted in the soil. The signal will be reflected from one rod to the other, then back to the meter. The meter measures the traveling time of the wave (the time between sending the wave and reflecting it). The wave traveling velocity can be computed by knowing the length of the cable and the length of the waveguide, which the measurement is averaged over. The information of the electromagnetic signal will be interpreted to volumetric water content on the screen of the digital meter.

The model of the TDR that was used for this study is TDR 100 / 200. This model has two different measurement options including the standard and the high clay mode. According to the manufacturer's recommendations, the high clay mode should be used when the soil clay content is high (>27%). This necessitated a further procedure, determining the percentage of clay contained within the soil. According to the procedures of the visual classification of soil sample-ASTM D2487, the classification of the soil at two stations B1 and B2 (figure 3.3) is poorly graded sandy soil with few different particle sizes and little or no fines, meaning that clay content in these soils is less that 27% and the TDR standard method is used.

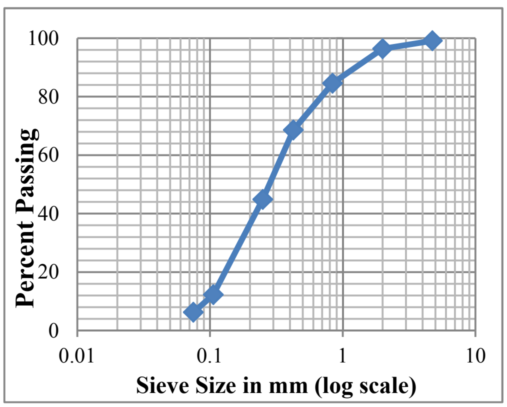
a b

Figure 3.3: Visual Classification of the Soil at Station: a) B1 and b) B2.

For the other three stations, visual classification was not clear, so a further investigation was required. Therefore, a sieve analysis was conducted based on the ASTM D 422 - standard test method for particle-size analysis of soils. This standard method states that fines, including clay, will pass through sieve # 200, which is the smallest sieve over the pan. The sieve analysis results (table 3.1) show that the percentages passed from sieve # 200 for the three samples are less than 10%. Therefore, the standard mode of the TDR is used for the VWC measure too.

Table 3.1: Clay Content in the Soil at the three Station: A1, A2, and A3.

Sieves #	Diameter (mm)	Sample A1			Sample A2			Sample A3		
		Mass of soil retained in gm.	Percent Retained	Percent Passing	Mass of soil retained in gm.	Percent Retained	Percent Passing	Mass of soil retained in gm.	Percent Retained	Percent Passing
4	4.75	2	1	99	4	1	99	4	1	99
10	2	9	4	96	15	4	96	12	4	96
20	0.84	39	15	85	62	15	85	49	16	84
40	0.43	79	31	69	126	31	69	99	31	69
60	0.25	138	55	45	221	54	46	173	55	45
140	0.11	219	88	12	351	86	14	275	87	13
200	0.075	234	94	6	380	93	7	293	93	7
Pan	---	250	100	0	410	100	0	315	100	0



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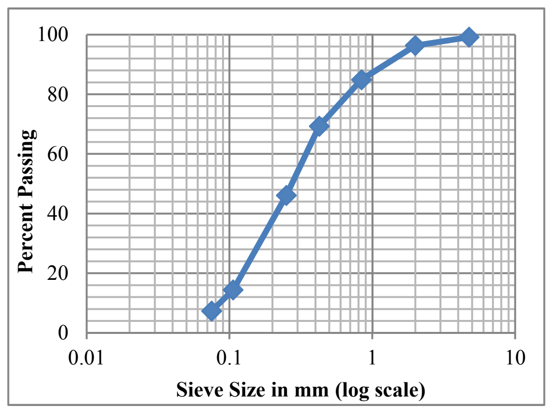

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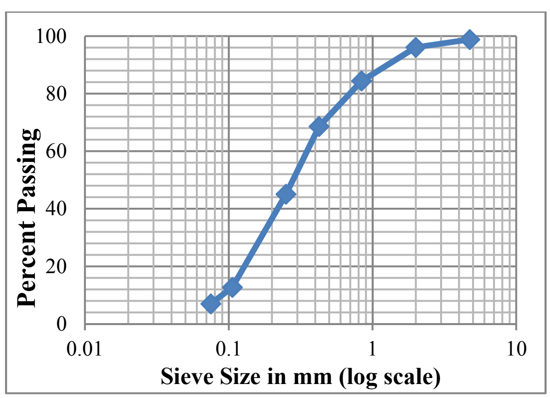

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Figure 3.4: Gradation of the Soil Sample from: a) Station A1, b) Station A2, and c) Station A3.

TDR was calibrated before the use. The manufacturer manual states that the TDR accuracy is ±3.0% VWC. Six samples of different soils were used to calibrate the TDR. The VWC% were measured by the TDR before samples were taken to a laboratory and the VWC% determined based on the standard test method for laboratory determination of water (moisture) content of soil and rock (ASTM 1992e). The results that are shown in Table (3.2) illustrate the acceptable accuracy of the TDR.

Table 3.2: The Results of the TDR Calibration.

Sample #	TDR, VWC%	laboratory, VWC%	Error VWC%
1	3.9	3.54	0.36
2	4.8	4.87	-0.07
3	14.8	13.26	1.54
5	13	15.1	-2.1
6	5	5.52	-0.52

3.3.2 Soil Suction Measurement (Tensiometer)

The tensiometer is an instrument that that reads soil suction directly in the field. It consists of a tube filled of water with a hollow ceramic tip attached on one end and a vacuum gauge and airtight seal on the other. The tensiometer should be installed at the desired depth in the soil where the ceramic tip is in good contact with the soil particles. The water in the tensiometer eventually comes to pressure equilibrium with the surrounding soil through the ceramic tip. The tip is always wet, so when installed in a dry soil the water moves from the tube through the tip pores into the soil creating a vacuum in the tube. As the soil becomes wet the vacuum in the tube decreases because water re-enter the tube from the tip. The tensiometer gauge

has a scale from 0-100 centibars. When the vacuum (tension) is created the gauge will move. The dryer the soil the higher reading will be obtained.

The tensiometer model that was used in this study is: Model 2900f1 “Quick Draw” Soilmoisture Probe. This portable tensiometer is produced to be easily carried and allow users to take many readings of the soil suction in the field throughout a relatively short time. This model (figure 3.5) has a carrying case that is it is made of strong lightweight extruded PVC. It contains all measurement required parts where it has a labeled place for each part of them. It has a sponge in the bottom at the probe place for keeping the probe wet and ready to use. The case is designed to enhance the shock resistance

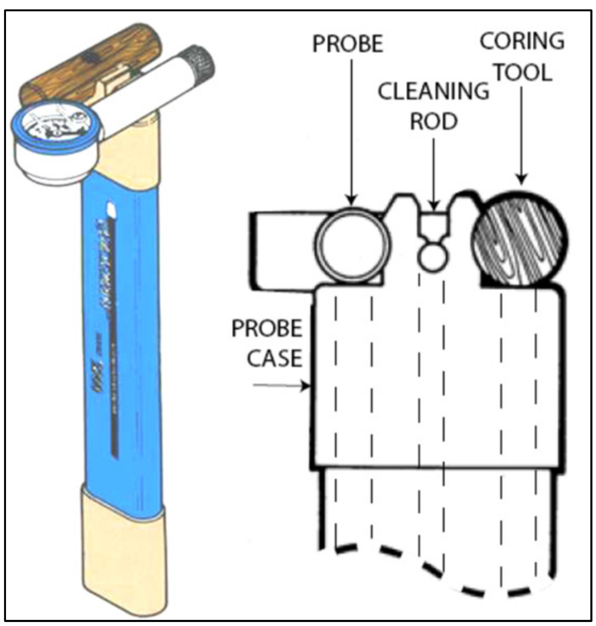

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Figure 3.5: The Tensiometer Carrying Case with Labeled Places for the Parts.

This tensiometer model has some additional excellences (figure 3.6): 1) the tube is thermally isolated to reduce the temperature impact while measuring. 2) It has a null knob located in the top of the rod and connected to the dial gauge via a horizontal tube. It is used to create vacuum in the thermal isolated tube and move the water from and into the soil through the ceramic tip for rapidly making an accurate soil suction measurement. 3) It comes with a coring tool that is made of chrome molybdenum steel and designed to match the taper of the ceramic tip for good soil contact. 4) It comes with a cleaning tool used to remove the sticky soil from the coring tool.

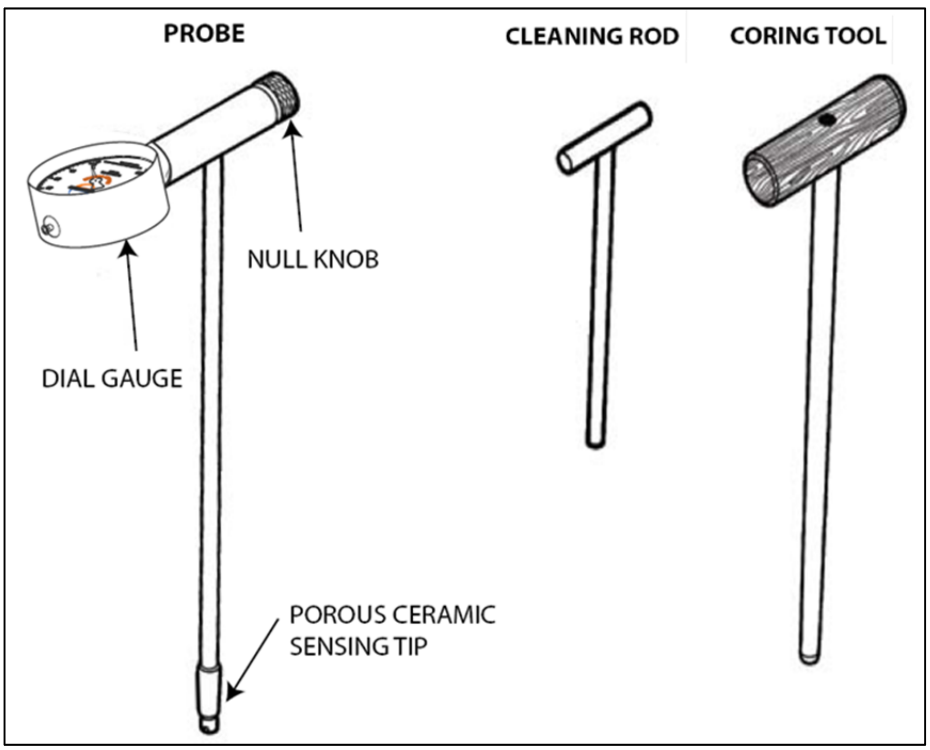


Figure 3.6: The Tensiometer Parts.

3.4 Samplers Construction

The samplers were built in the sites in order to measure the volumetric water content and the soil suction of the soil water at five constant stations at the same soil depth. To protect this station and facilitate frequently taking the measurements, a special methodology was followed to build these stations. The construction of the stations started with preparing a 2-gallon bucket and cut it at 6 inches to be opened before installation. After that a 6-inches hole was excavated to take the prepared bucket (figure 3.7). For safety, stations should remain closed by the buckets' lids when no measurements are being taken.

Figure 3.7: Measurement Station.

3.5 Stations' Description

Three of the five stations were installed at the residential home (figure 3.8) while the other two stations installed in a desert location near to El Paso. The landscape of the residential home has been equipped with a small French drain, which is laid next to the carport to convey the dripping rainwater from the roof and prevent it from accumulating in there. In addition, the uncultivated spaces in the landscape are covered with permeable weed barrier and gravel mulch.

Figure 3.8: The Locations of the Sampling Stations at the Residential Home.

Station A1: it is located in the southeast corner of the residential house yard just next to the carport. The station is close to the water drip line when raining. However, there is a French drain laid under the water drip line (figure 3.9).

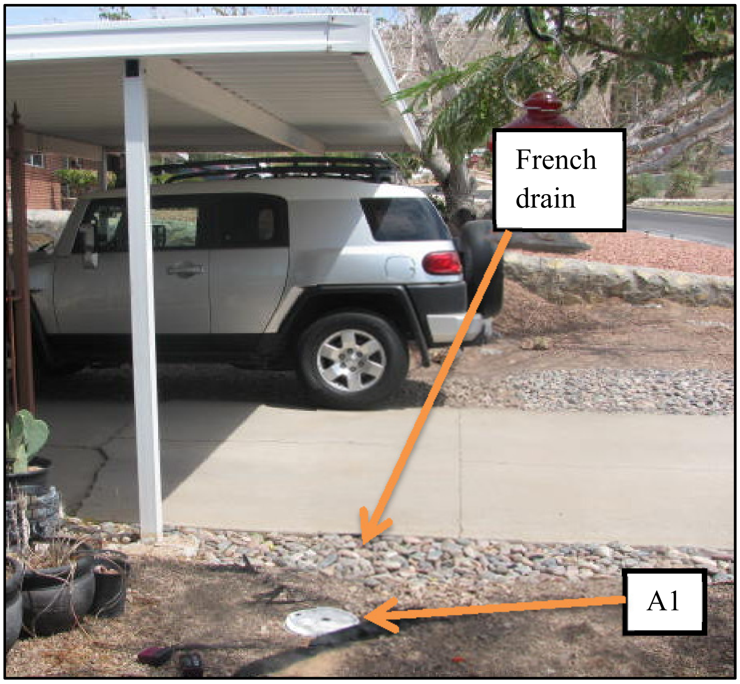


Figure 3.9: Station A1.

Station A2 (figure 3.10): it is located in the southwest side of Walton house yard. This station falls into the middle of a small natural depression. This depression captures runoff from the adjacent area.

Figure 3.10: Station A2.

Station A3 (figure 3.11). It is located in the northwest corner of the residential house. It is directly placed under the water drip line from the roof.

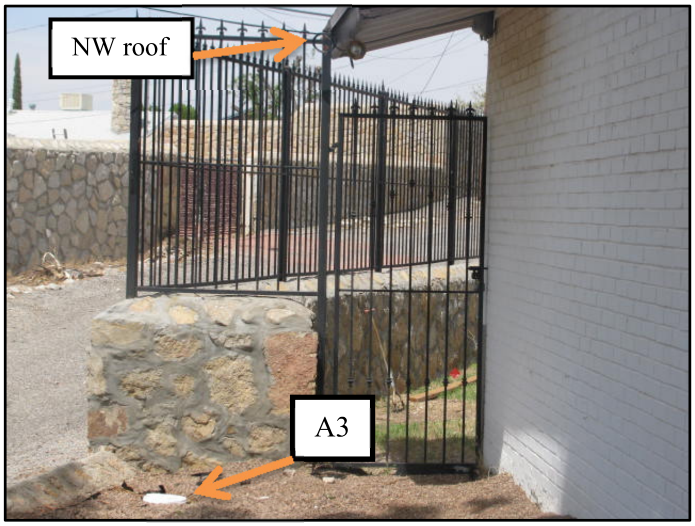


Figure 3.11: Station A3.

Stations B1and B2 are placed in a desert location near to El Paso. B1 was placed downhill by a desert shrub while B2 was placed uphill by another desert shrub.

3.6 Measuring Process

Measurements of water content (TDR readings) and soil suction (Tensiometer readings) were taken throughout a period of time from the beginning December, 2010 to the end of September, 2011. During the drought period, the measurements were taken once every one to two weeks. However, when the rainy season started, daily measurements were conducted. The reason is that in the dry season the readings were slightly changing from week to the other. When the rain started and the soil is r-wetted the measurements changed quickly, so the readings were taking every day until the change slowed down.

The measurement of the TDR is averaged over the waveguide, which is controlled by the TDR rod length. On the other hand, the soil suction was measured for the soil surrounding the ceramic tip whose length is shorter than the TDR rod length. To be consistent and reliable over the entire measuring period, the tensiometer was inserted at a soil depth where the center of the ceramic tip meets the center of the TDR rod. Therefore, the coring tool of the tensiometer was marked at the distance that should be inserted. Moreover, a raising plastic tube was made to hold the tensiometer at the desired depth all the time (figure 3.12).

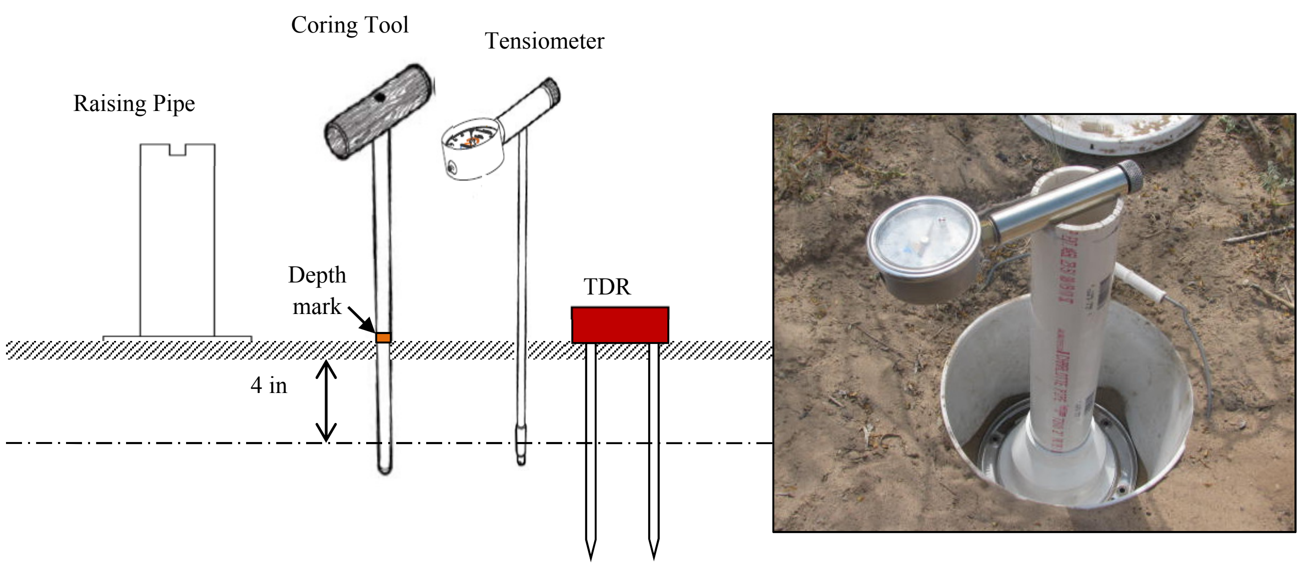


Figure 3.12: The Constant Measuring Depth.

3.6.1 TDR Measuring Process

Making a measurement using the TDR is simple and easy. However, there are some precautions should be considered in order to obtain accurate readings.

1. Attention should be paid to the meter screen immediately after turning the meter on to make sure that the battery is adequately charged. The battery charge level will be

displayed for short time before the other setting options appear on the meter screen. The meter should be turned off as soon as the measurement operation is finished to keep the battery charged for longer period of time.

2. Before use, check should be conducted on the TDR setting, including the measuring mode and the probe length, because this setting can be changed unintentionally by a light touch and leads to wrong reading.
3. Users should make sure that the probe rods are tightly installed to their base.
4. Care must be taken when inserting the rods into the soil. A constant downward pressure should be applied all the way till the rods are completely inserted. This step ensures that no air pocket would be created around the rods by wiggling them into the soil leading to a reading reduce. In addition, the rods should be inserted as parallel to one another as possible to protect them from any damage may occur during the operation.
5. The rods have to be totally dry before use, so they should be wiped by dry clean tissue before reinserting them in a new location. Wet rods will result in high readings.

3.6.2 Tensiometer Measuring Process

Conducting a measurement using the tensiometer is more complicated than measuring the water content by the TDR. There are many steps have to be taken prior, during, and after the measuring operation:

The following steps have to be taken prior to measuring,

1. Venting and adjusting the dial gauge: the tensiometer dial gauge is adjusted and sealed at sea level; therefore, in areas at higher elevation the gauge pointer may point a reading higher than zero because of the lower atmospheric pressure. For venting and adjusting the

gauge, two simple steps needed to be made. First, user should press a vent pin located at the top of the gauge in order to release any collected air, figure (3.13). After that, if the pointer still does not indicate to zero, the screwdriver located on the face of the gauge should be slightly turned clockwise or counterclockwise, based on the pointer position, up or down to the zero. This step should be repeated until the pointer is on zero.

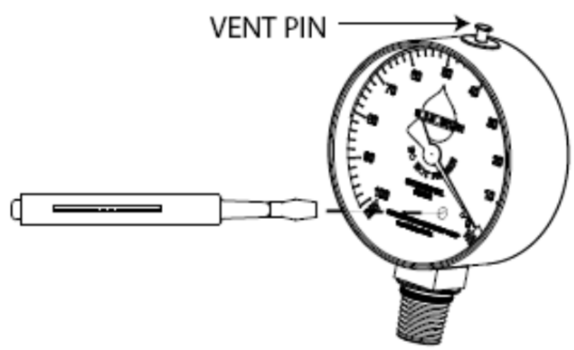


Figure 3.13: Venting and Adjusting the Dial Gauge.

2. The probe filling: this process is required prior to the first use or if the ceramic probe is exposed to the air for prolonged time and dried out. This process is essential to remove any air existing in the probe. The air may significantly affect the reading and decrease the sensitivity of the ceramic tip. The procedures of this process are explained in detail in the instrument's manufacturer manual.
3. The ceramic tip should be kept wet and ready to use at any time. Therefore, if not in use the probe should be inserted in the carrying case while the carrying case is held vertically and the sponge in its bottom is wet. For this reason, the sponge should be rinsed at least once a week.

After taking the steps prior to measuring in consideration, the following steps should be followed during and after measuring:

1. The first step of making an accurate measurement is to make a vertical hole into the soil using the coring tool to the desired depth.
2. After coring the hole and before inserting the probe into the soil, the null knob should be turned clockwise as far as it will go and then returned counterclockwise half turn. This operation gives the probe an appropriate scope for the null knob while making the measurement. When turning the null knob counterclockwise, the pointer will rise up from zero to around 50 centibars before it comes back to zero in about 30 seconds. The probe should not be taken out from the carrying case until the gauge pointer is on zero.
3. Water always moves from the higher energy level to the lower energy level. The tensiomenter probe works as a fully saturated soil section, so if the soil is also saturated, the energy in the probe and in the soil will be equiponderant and the water will not move into or from the soil and the dial gauge pointer will remain on zero. On the other hand, if the soil is below the saturation level, water will transfer from the probe into the soil trough the ceramic tip and create a vacuum in the probe. This vacuum will be interpreted to centibars on the dial gauge as a soil suction force. Whenever the null knob is turned either clockwise or counterclockwise, the water will be forced to move from or into the soil, respectively. The null knob helps to achieve the equilibrium in a short period of time.
4. Care should be taken while inserting the probe into the soil because it has to be inserted vertically in the right place and that should be as quickly as possible without long exposure to the air. For loose soil, such as poor graded sand, the probe should be inserted into the soil without coring a hole. The raising tube helps in this situation to hold the probe at the desired depth.

5. As soon as the probe is inserted into the soil, the pointer will move from zero to a certain value of centibars unless the soil is saturated. In this case, the pointer will remain on zero. The gauge should be monitored for 60 seconds while tapping on the gauge every 10-15 seconds. Tapping on the gauge helps get rid of any air bubbles may intervene. The gauge here points the initial reading (point 1).
6. Now, the null knob should be turned counterclockwise to bring the pointer to one-half times of the initial value. The gauge pointer should be tapped right away after the pointer stopped on the new reading. This tapping usually makes the pointer moves up slightly and follows the previous pointer movement. This procedure should be applied every time the null knob is turned either clockwise or counterclockwise. The reading on which the pointer stopped is the new reading (point 2). At this moment, the pointer should be monitored for at least 30 seconds. When the soil is dry, this step takes longer time than the when the soil is wet. It has been noticed that the sensitivity of the tensiometer decreases with dry soils.
7. If the pointer moves down (this movement is very small; that is why the pointer should be carefully watched), that means that the right reading is between the initial reading (point 1) and the last reading (point 2), so the null knob should be turned clockwise to bring the pointer down half way between the two readings (point 3) and monitored again for at least 30 seconds while tapping the gauge. After that, if the pointer does not move that means that the right reading has been achieved. However, if the pointer moves up or down that means that the right reading is between point 3 and point 2 or point 1 respectively. This procedure should be repeated till the pointer is on the right reading and does not move up or down any more.

8. If the pointer shortly moves up from point 2, the null knob should be immediately turned counterclockwise to move the pointer up 10 centibars to a new value (point4). Then the pointer should be monitored for at least 30 seconds. If the pointer moves down, that means the right reading is between point 2 and point 4 and same procedures of the previous point should be followed. Otherwise, the null knob should be directly turned counterclockwise to move the pointer up another 10 centibars to a new value (point5) and etcetera.
9. When the equilibrium is close to be achieved, the pointer movement becomes slower than the beginning because the water movement trough the ceramic tip becomes slower. Therefore, more time should be spent waiting for the tensiometer to response.
10. When finishing the measuring, the probe should be carefully taken out from the hole and wiped by clean dry tissue before returned to the carrying case in the place specified and marked for it. This should be done as quickly as possible without exposing the ceramic tip to the air for long time and drying it out.

4. Results and Discussion

4.1 Introduction

The results of the Low Impact Development (LID) design show that the designed Integrated Management Practices (IMP) system for the single family residence can capture the excessive runoff resulting from the lot surface conversion from permeable to impermeable surface. This keeps the hydrology of the area as it was prior to development. They, also, show that an efficient passive landscape can be implemented in the lot where a large part of the lawn area can be passively vegetated with native and high drought tolerant shrubs and trees after root establishment. In addition, the landscaping cost analyses show that significant savings can be achieved throughout the following years, especially after root establishment is complete. These results are applicable for the three representative cities of the study area with some minor differences, due to the different climatological conditions and the water utility cost in these cities. The analyses of data that were collected from the different samples in El Paso, TX illustrate the relationship between the soil water content and the soil suction, and show how the landscaping practices can store water for future plant use.

4.2 Low Impact Development Practices

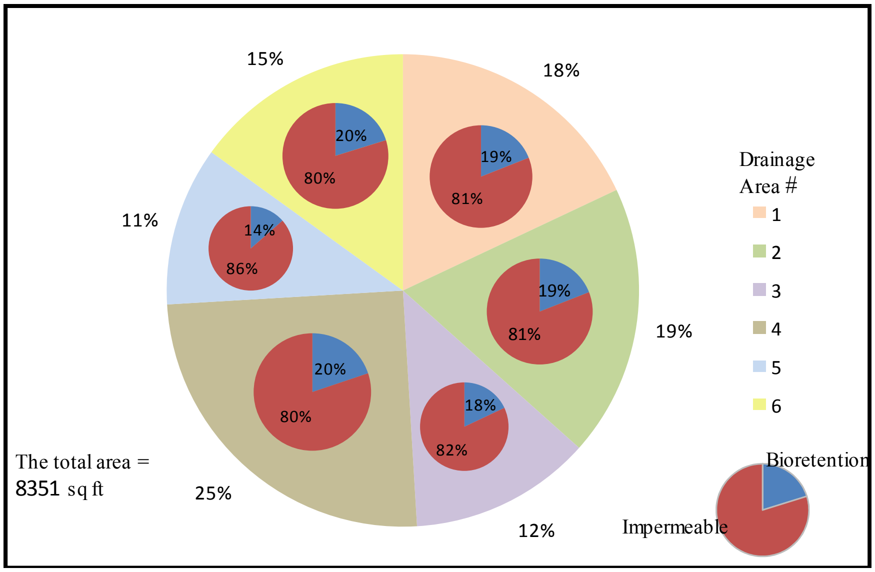
The size of the bioretention units differs between locations because of the variation in the climate, geography, and topography of these cities. When designing multiple bioretention units within one city, however, it differs from one house plan to another because of the variation in the size and the properties of the runoff capture area. The size of bioretention units is controlled by the amount off runoff discharge that is directed toward these units. The amount of the runoff depends on the surface type and the size of the area surrounding the bioretention units. When the

permeability of the surface is low, a large amount of runoff is generated because small surface runoff soaks through the surface into the soil. In addition, the size of the bioretention is controlled by the intensity of the rain storms. When the storms occur in succession, and the runoff that is generated from a storm and captured in the bioretention units does not have an adequate time to infiltrate before another storm arrives, a larger size of bioretention is needed.

The results of this study, as presented in the following graphs and tables, show that when the street is included in the runoff capture area (option 2 (Lot + Street)), a 63% larger bioretention cell is needed to be installed in Drainage Area1 than the one that should be installed if the street is not included (option 1). The increase in the size is for the runoff coming from the street to be preserved. This larger bioretention cell provides more stored water for the vegetation and will increase the green area in the house yard.

Table 4.1: Sizes of LID Practices in El Paso City for Both Options.

Drainage Area #	Option 1 (Lot)			Option 2 (Lot + Street)		
	Total Drainage area, sq-ft	Capture area, sq-ft	Bioretention area, sq-ft	Total Drainage area, sq-ft	Capture area, sq ft	Bioretention area, sq-ft
1	1503	1217	286	2327	1861	466
2	1554	1245	309	1554	1245	309
3	1039	852	187	1039	852	187
4	2089	1675	414	2089	1675	414
5	911	787	123	911	787	123
6	1257	1002	253	1257	1002	253
Total	8351	6778	1573	9175	7423	1753



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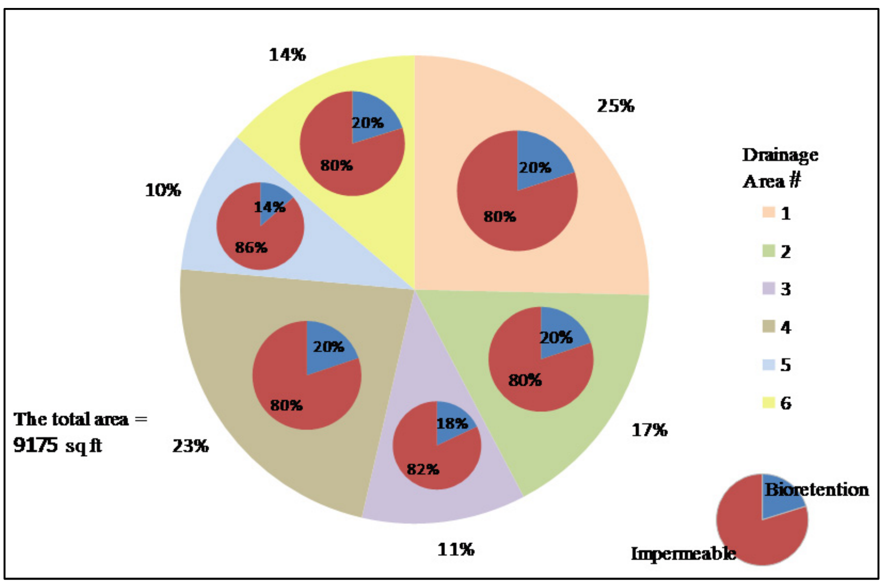

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Figure 4.1: The Bioretention Areas in the Every Drainage Area El Paso. a) Option 1 (Lot), and b) Option 2 (Lot + Street)

The following tables (table 4.2 and table 4.3) present the results of the design in Phoenix and Albuquerque respectively. The areas of the bioretention cells in Albuquerque and Phoenix have approximately the same sizes, which are smaller than what resulted in El Paso. According to the statistical analysis for the climatologic data of each of these cities, Albuquerque has the

highest number of effective storms, whose precipitation exceeds the initial abstraction and causes runoff, followed by El Paso and then Phoenix. However, the maximum precipitation of the events that occurred in Albuquerque is smaller than that of the events occurred in El Paso. These events, also, have a better distribution over the time. Subsequently, runoff generated from an event will be captured in the bioretention unites and allowed to infiltrate and evaporate in a longer period of time before the next storm will arrive. Therefore, the smaller size of bioretention depression is adequate.

Table 4.2: Sizes of LID Practices in Albuquerque City for Both Options.

Drainage Area #	Option 1 (Lot)			Option 2 (Lot + Street)		
	Total Drainage area, sq-ft	Capture area, sq-ft	Bioretention area, sq-ft	Total Drainage area, sq-ft	Capture area, sq ft	Bioretention area, sq-ft
1	1503	1242	260	2327	1900	427
2	1554	1270	284	1554	1270	284
3	1039	869	170	1039	869	170
4	2089	1710	379	2089	1710	379
5	911	771	140	911	771	140
6	1257	1023	233	1257	1023	233
Total	8351	6885	1466	9175	7543	1633
	Bioretention/Capture		21%			

The total size of bioretention areas in Phoenix is nearly the same as the total size of bioretention areas in Albuquerque, even though it has a lower number of effective storms as well as higher temperatures. This is because the precipitation events that occurred in Phoenix are intensive and accumulate on each other in a shorter period of time, and the runoff that is generated from these storms require a larger retention size.

Table 4.3: Sizes of LID Practices in Phoenix City for Both Options.

Drainage Area #	Option 1 (Lot)			Option 2 (Lot + Street)		
	Total Drainage area, sq-ft	Capture area, sq-ft	Bioretention area, sq-ft	Total Drainage area, sq-ft	Capture area, sq ft	Bioretention area, sq-ft
1	1503	1242	261	2327	1900	427
2	1554	1270	284	1554	1270	284
3	1039	869	170	1039	869	170
4	2089	1709	380	2089	1710	380
5	911	770	141	911	770	141
6	1257	1023	233	1257	1023	233
Total	8351	6884	1468	9175	7541	1635

4.3 Landscape Results

The landscape results include two parts: 1) the area of passive landscape that can be grown using the water stored in the bioretention cells implemented in the lawn; and 2) the differential cost between the passive landscape and the conventional landscape.

4.3.1 Covered Areas

The area of landscape, which can be passively grown after root establishment, differs based on the number of shrubs and trees that are included in the yard of the house. The following results present the percentage of the crown green area that can be covered by the stored water captured in the bioretention units for the two capture area options in El Paso. Landscapes usually contain both trees and shrubs, so green crown areas of different trees and shrubs percentages are shown in following table and graphs.

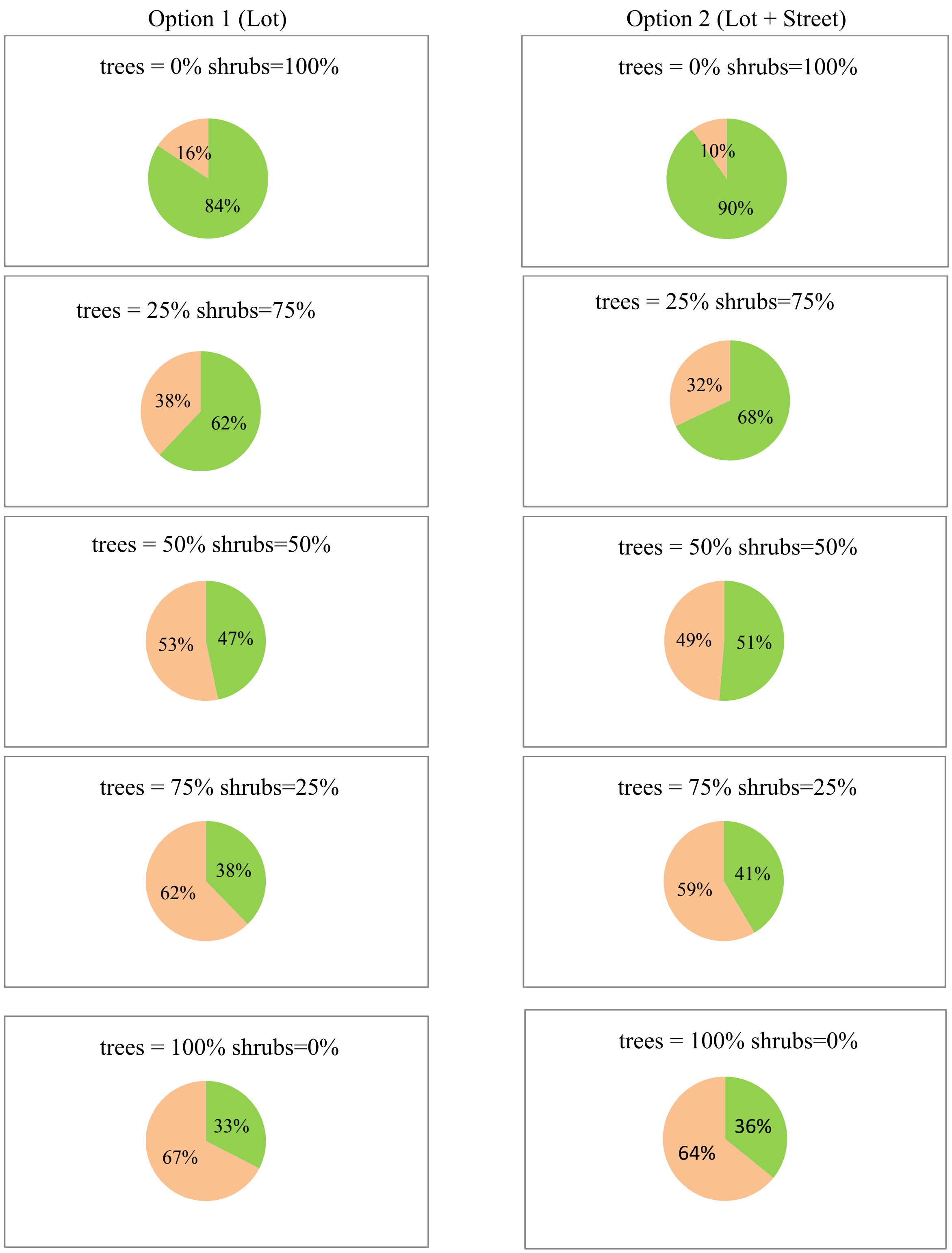

Figure 4.2: Green Area (Vegetation's Crown Area) in the Lawn for the Two Capture-Area Options in El-Paso.

The results show that the percentage of the green area in the lawn drops from 84% and 90% when no trees are grown in the yard to 33% and 41% when no shrubs are included in option 1 (Lot) and option 2 (Lot + Street) respectively.

Table 4.4: El Paso Crown Green Area for Option 1 (Lot).

Drainage Area #	Green Area (Vegetation's' Crown Area), sq ft				
	trees=0% and shrubs=100%	trees=25% and shrubs=75%	trees=50% and shrubs=50%	trees=75% and shrubs=25%	trees=100% and shrubs=0%
1	800	540	400	325	280
2	820	565	415	335	290
3	550	370	275	220	190
4	1050	750	560	450	390
5	273	273	235	190	165
6	527	465	345	280	240
Sum	4020	2963	2230	1800	1555
Crown Area/Lawn	84%	62%	47%	38%	33%
Crown Area/Total Area	48%	35%	27%	22%	19%

Option 2 (Lot + Street) provides more runoff for the lawn; therefore, more shrubs and trees can be grown.

Table 4.5: El Paso Crown Green Area for Option 2 (Lot + Street).

Drainage Area #	Green Area (Vegetation's' Crown Area), sq ft				
	trees=0% and shrubs=100 %	trees=25% and shrubs=75 %	trees=50% and shrubs=50 %	trees=75% and shrubs=25 %	trees=100 % and shrubs=0%
1	1090	820	620	505	435
2	820	565	415	335	290
3	550	370	275	220	190
4	1050	750	560	450	390
5	273	273	235	190	165
6	527	465	345	280	240
Sum	4310	3243	2450	1980	1710
Crown Area/Lawn Area	90%	68%	51%	41%	36%
Crown Area/Total Area	52%	39%	29%	24%	20%

The next tables contain the results of the landscape design for Albuquerque and Phoenix, respectively.

Table 4.6: Albuquerque Crown Green Area for Option 1 (Lot).

Drainage Area #	Green Area (Vegetation's' Crown Area), sq ft				
	trees=0% and shrubs=100%	trees=25% and shrubs=75%	trees=50% and shrubs=50%	trees=75% and shrubs=25%	trees=100% and shrubs=0%
1	700	500	395	320	285
2	750	525	415	340	305
3	470	335	265	220	195
4	950	690	540	450	400
5	273	273	225	185	170
6	527	435	340	280	250
Sum	3670	2758	2180	1795	1605
Crown Area/Lawn	77%	58%	46%	38%	34%
Crown Area/Total	44%	33%	26%	21%	19%

Table 4.7: Albuquerque Crown Green Area for Option 2 (Lot + Street).

Drainage Area #	Green Area (Vegetation's' Crown Area), sq ft				
	trees=0% and shrubs=100%	trees=25% and shrubs=75%	trees=50% and shrubs=50%	trees=75% and shrubs=25%	trees=100% and shrubs=0%
1	1090	775	605	500	450
2	750	525	415	340	305
3	470	335	265	220	195
4	950	690	540	450	400
5	273	273	225	185	170
6	527	435	340	280	250
Sum	4060	3033	2390	1975	1770
Crown Area/Lawn	85%	64%	50%	41%	37%
Crown Area/Total	49%	36%	29%	24%	21%

Table 4.8: Phoenix Crown Green Area for Option 1 (Lot).

Drainage Area #	Green Area (Vegetation’s' Crown Area), sq ft				
	trees=0% and shrubs=100%	trees=25% and shrubs=75%	trees=50% and shrubs=50%	trees=75% and shrubs=25%	trees=100% and shrubs=0%
1	680	450	335	270	230
2	700	475	350	285	245
3	450	305	225	183	158
4	920	630	470	380	325
5	273	225	180	145	127
6	527	390	290	235	202
Sum	3550	2475	1850	1498	1287
Crown Area/Lawn	74%	52%	39%	31%	27%
Crown Area/ Total	43%	30%	22%	18%	15%

Table 4.9: Phoenix Crown Green Area for Option 2 (Lot + Street).

Drainage Area #	Green Area (Vegetation’s' Crown Area), sq ft				
	trees=0% and shrubs=100%	trees=25% and shrubs=75%	trees=50% and shrubs=50%	trees=75% and shrubs=25%	trees=100% and shrubs=0%
1	1020	705	525	425	365
2	700	475	350	285	245
3	450	305	225	183	158
4	920	630	470	380	325
5	273	225	180	145	127
6	527	390	290	235	202
Sum	3890	2730	2040	1653	1422
Crown Area/Lawn	81%	57%	43%	35%	30%
Crown Area/ Total	47%	33%	24%	20%	17%

There are some observations that can be seen in the results. First, the total area of the passive landscape resulted in Phoenix is smaller than that in Albuquerque, even though the total area of the bioretention units in Albuquerque and in Phoenix is approximately the same. Second,

when shrubs dominate the lawn area, the total landscape area in Albuquerque is smaller than that in El Paso and larger than in Phoenix. However, when the trees' percentage is equal to or higher than the percentage of the shrubs in the landscape, Albuquerque can provide a larger green area than the other two cities. These differences can be related to the difference in climate between the cities and also to the difference in root depth between trees and shrubs. The root depth controls the depth of the water storage where the maximum water storage falls between the field capacity and wilting point. In addition, when the trees dominate the lawn area El Paso and Phoenix can provide a smaller green area because they have higher temperatures than Albuquerque; therefore, the evapotranspiration rate will be higher thus smaller number of trees can be passively grown.

4.3.2 Landscape Differential Cost

The analysis of differential cost between the conventional landscape and the designed passive landscape show that considerable savings can be achieved over time. These savings differ between cities, based on: 1) water rate in every city; and 2) the passive landscape area that can be grown in them. In El Paso, up to $32,000 can be saved over the course 10 years. The amount of savings will be approximately $31,000 and $30,000 in Phoenix and Albuquerque, respectively. These values represent approximately 72-71% of the original cost of the conventional landscape over 10 years, and about 50% of the annualized cost can be saved in the three cities. The following tables and graphs illustrate the results:

Table 4.10: Conventional Landscape Cost in El Paso.

Conventional Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,000
Gallons of Water Used Annually	20,000	49,000
Annual Water Cost Due to Irrigation	$88	$221
Annual Flower Bed Maintenance	$856	$1,700
Annual Turf Maintenance	$63	$92
Annual Shrub and Ground Cover Maintenance	$251	$401
Annual Tree Maintenance	$84	$351
Landscape Firm's Travel Cost	$0	$0
Landscape Firm's Profit	$0	$0
Annual Maintenance Cost	$1,253	$2,600
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$1,300**	**$3,000**
Total 3 Year Cost	**$12,000**	**$24,000**
Total 6 Year Cost	**$16,000**	**$33,000**
Total 10 Year Cost	**$22,000**	**$44,000**
Annualized Cost (30 year loan at 5% interest)	**$1,900**	**$3,900**

Table 4.11: Passive Landscape Cost in El Paso.

Passive Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,000
Rebate	$0	$0
Net Initial Cost	$8,100	$16,000
Gallons of Water Used Annually	$0	$0
Annual Water Cost Due to Irrigation	$0	$0
Annual Flower Bed Maintenance	$0	$0
Annual Turf Maintenance Cost	$0	$0
Annual Shrub and Ground Cover Maintenance	$313	$501
Annual Tree Maintenance	$104	$438
Landscape Contractor's Travel Cost	$0	$0
Landscape Contractor's Profit	$0	$0
Annual Maintenance Cost	$418	$939
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$418**	**$939**
Total 3 Year Cost	**$9,300**	**$19,000**
Total 6 Year Cost	**$11,000**	**$22,000**
Total 10 Year Cost	**$12,000**	**$25,000**
Annualized Cost (30 year loan at 5% interest)	**$950**	**$2,000**

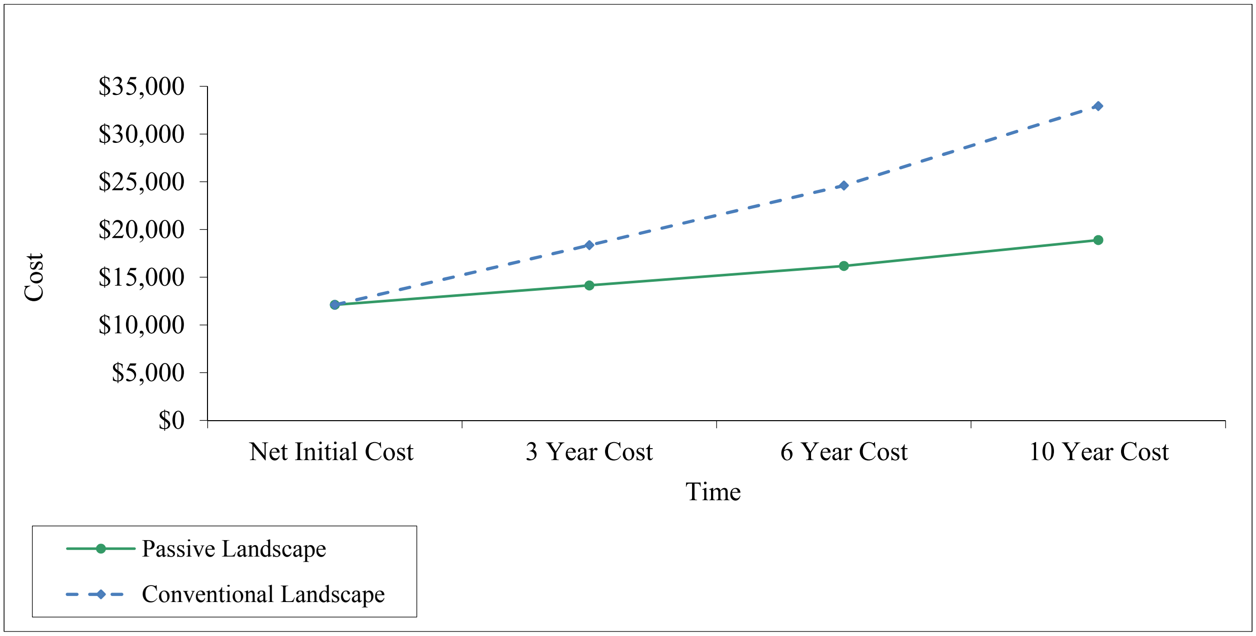

Figure 4.3: Average Total Cost over Time in El Paso. This graph is generated using the average of the high and low cost estimates for each type of landscape.

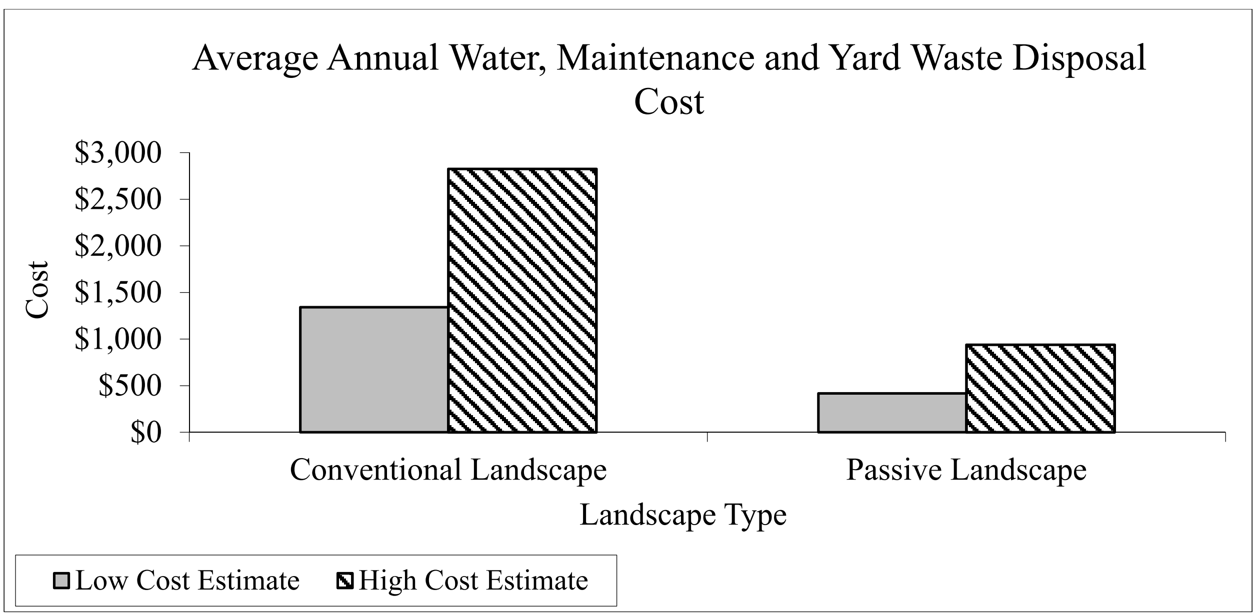

Figure 4.4: Average Annual Water and Maintenance Cost in El Paso.

Table 4.12: Conventional Landscape Cost in Albuquerque.

Conventional Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,076
Gallons of Water Used Annually	19,000	49,000
Annual Water Cost Due to Irrigation	$22	$54
Annual Flower Bed Maintenance	$856	$1,762
Annual Turf Maintenance	$63	$92
Annual Shrub and Ground Cover Maintenance	$251	$401
Annual Tree Maintenance	$84	$351
Landscape Firm's Travel Cost	$0	$0
Landscape Firm's Profit	$0	$0
Annual Maintenance Cost	$1,200	$2,606
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$1,200**	**$3,000**
Total 3 Year Cost	**$12,000**	**$24,000**
Total 6 Year Cost	**$16,000**	**$32,000**
Total 10 Year Cost	**$21,000**	**$43,000**
Annualized Cost (30 year loan at 5% interest)	**$1,800**	**$3,700**

Table 4.13: Passive Landscape Cost in Albuquerque.

Passive Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,000
Rebate	$0	$0
Net Initial Cost	$8,100	$16,000
Gallons of Water Used Annually	$0	$0
Annual Water Cost Due to Irrigation	$0	$0
Annual Flower Bed Maintenance	$0	$0
Annual Turf Maintenance Cost	$0	$0
Annual Shrub and Ground Cover Maintenance	$313	$501
Annual Tree Maintenance	$104	$438
Landscape Contractor's Travel Cost	$0	$0
Landscape Contractor's Profit	$0	$0
Annual Maintenance Cost	$418	$939
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$418**	**$939**
Total 3 Year Cost	**$9,400**	**$19,000**
Total 6 Year Cost	**$11,000**	**$22,000**
Total 10 Year Cost	**$12,000**	**$25,000**
Annualized Cost (30 year loan at 5% interest)	**$950**	**$2,000**

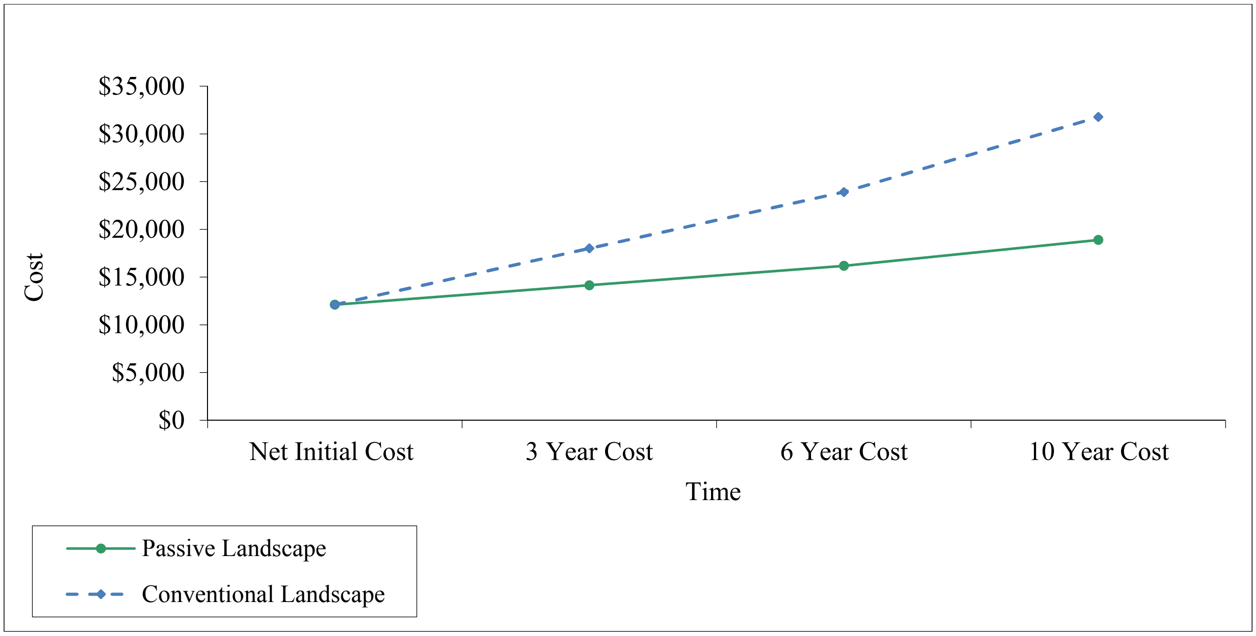

Figure 4.5: Average Total Cost over Time in Albuquerque.

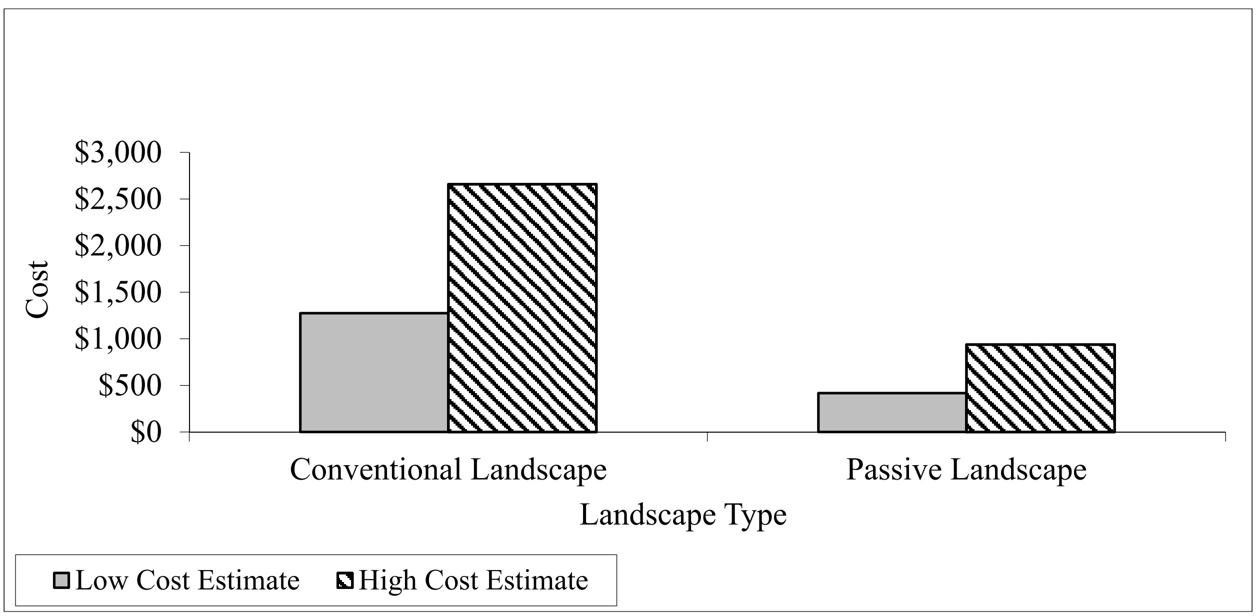

Figure 4.6: Average Annual Water and Maintenance Cost in Albuquerque.

Table 4.14: Conventional Landscape Cost in Phoenix.

Conventional Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,000
Gallons of Water Used Annually	20,000	49,000
Annual Water Cost Due to Irrigation	$71	$177
Annual Flower Bed Maintenance	$856	$1,700
Annual Turf Maintenance	$63	$92
Annual Shrub and Ground Cover Maintenance	$251	$401
Annual Tree Maintenance	$84	$351
Landscape Firm's Travel Cost	$0	$0
Landscape Firm's Profit	$0	$0
Annual Maintenance Cost	$1,200	$2,600
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$1,300**	**$2,700**
Total 3 Year Cost	**$12,000**	**$24,000**
Total 6 Year Cost	**$16,000**	**$33,000**
Total 10 Year Cost	**$21,000**	**$44,000**
Annualized Cost (30 year loan at 5% interest)	**$1,900**	**$3,800**

Table 4.15: Passive Landscape Cost in Phoenix.

Passive Landscape	Low Cost Estimate	High Cost Estimate
Initial Cost	$8,100	$16,000
Rebate	$0	$0
Net Initial Cost	$8,100	$16,000
Gallons of Water Used Annually	$0	$0
Annual Water Cost Due to Irrigation	$0	$0
Annual Flower Bed Maintenance	$0	$0
Annual Turf Maintenance Cost	$0	$0
Annual Shrub and Ground Cover Maintenance	$313	$501
Annual Tree Maintenance	$104	$438
Landscape Contractor's Travel Cost	$0	$0
Landscape Contractor's Profit	$0	$0
Annual Maintenance Cost	$418	$939
Annual Yard Waste Disposal Cost	$0	$0
Annual Total Cost	**$418**	**$939**
Total 3 Year Cost	**$9,400**	**$19,000**
Total 6 Year Cost	**$11,000**	**$22,000**
Total 10 Year Cost	**$12,000**	**$25,000**
Annualized Cost (30 year loan at 5% interest)	**$950**	**$2,000**

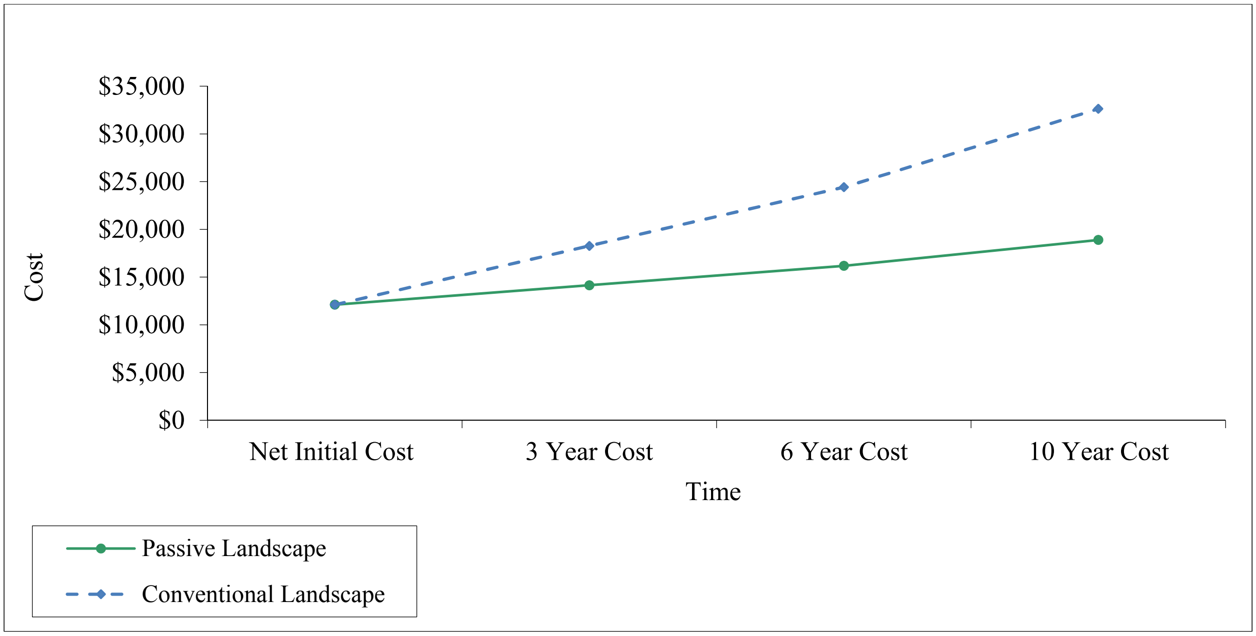

Figure 4.7: Average Total Cost over Time in Phoenix.

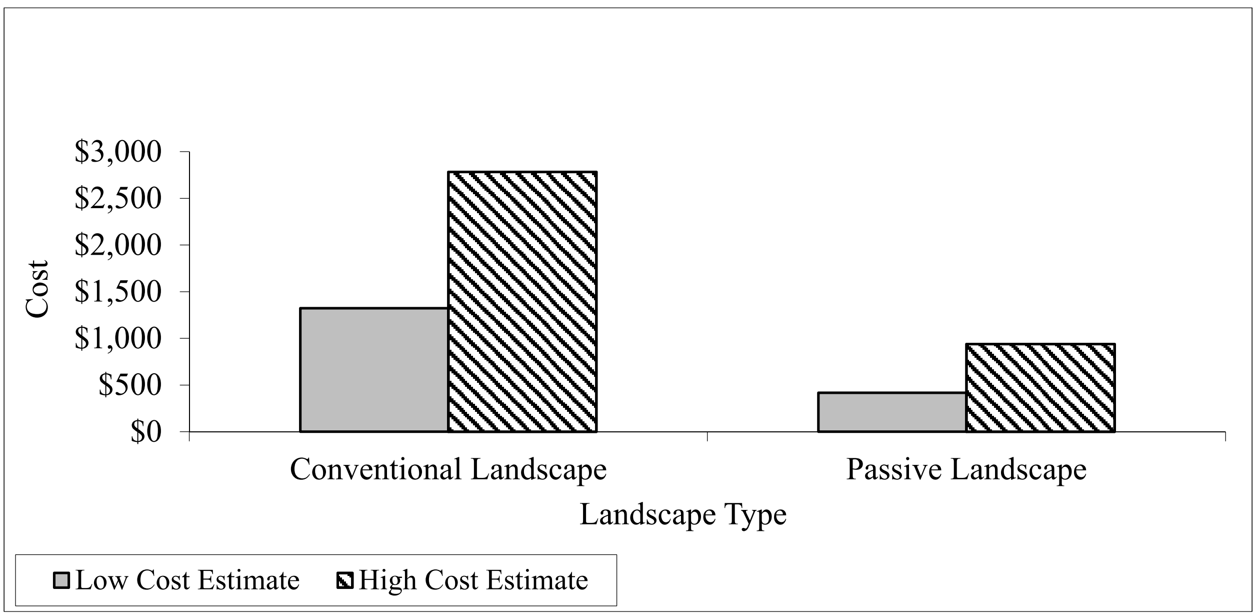

Figure 4.8: Average Annual Water and Maintenance Cost in Phoenix.

4.4 Results of sampling data

The soil suction and water content data, which were collected from five stations throughout ten months from December, 2010 to the end of September, 2011, show that every station has different results based on the circumstances of its location and the soil properties at this location. During these ten months, El Paso passed through a long drought period from the beginning of February, 2011 through the middle of July, 2011. Throughout this period of time, the soil suction reached the highest level while the water content dropped to the lowest level. However, when some large precipitation events occurred, the water content in the soil increased and the soil suction dramatically dropped. The results show that the relationship between the soil suction and the water content is an inverse one.

Generally, the data collected from the three stations(A1, A2 and A3), installed in the yard of the single family residence at Turney Drive, show that the soil got saturated more times than the soil at the two other stations that installed in the desert (B1 and B2) even though the same precipitation events were received by the all stations. Moreover, the data show that the soil at these three stations hold the water for longer time than the soil at the other two stations. The differences are due to the function of the simple LID practices including the gravel mulch and French drain that are implemented in the house yard. Also, the variance in the soil properties has a say in the data differences, where the sandy soil in the desert loses the water faster than the amended soil in the house yard.

For the three stations that installed at the residential home, the soil properties are similar for all stations; however, there are some differences in the water content and soil suction measurements of these stations. It can be clearly seen on the following graphs that the water

content and soil suction values at station A1 did not change as quickly as the values at the other two stations. This is because the French drain that has been installed near station A1 captures the water that dropping from the southeast roof and prevents it from running off toward the station. Therefore, the dropping water infiltrates into the soil from the French drain sides at a relatively distant point from the station. On the other hand, the soil at station A3 gets saturated easily because it is located directly under the dropping water from the northwest roof. Although the lid, which covers the station, prevents the dropping water from accessing the soil directly, the water infiltrates into the soil at the closest point possible. The measurements at station A2 changed with larger values and more times than the measurements at station A1 but it changed fewer times than the measurements at stationA3. This is because it is located in the middle of a small depression in the southwest corner of the residential home where more water runs off toward the depression and infiltrates at the closest point to the stations.

The landscape in the yard of the residential home is not fully equipped with low impact practices and it is installed as the designed landscape for this study because of the limited fund. However, the measurements give a very high indication that low impact approaches can successfully capture a sufficient amount of water for the passive landscape. When the runoff, which is generated from the impermeable surfaces such as the house roof, is captured at the closest point to the source and directed to the landscape, any precipitation event will beneficially cooperate in providing water to the vegetation.

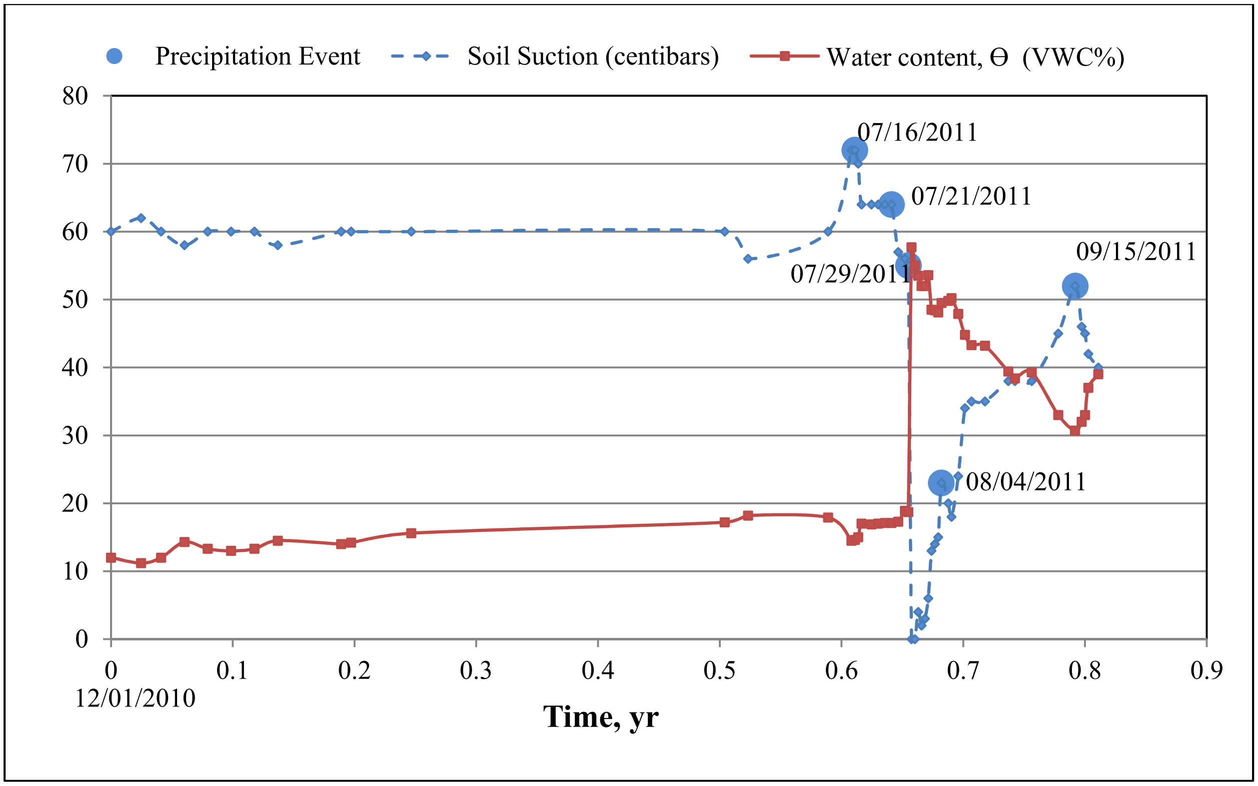

Figure 4.9: The Measured Water Content and Soil Suction at Station A1 Located at SE Corner of the Residential Home at Turney Drive.

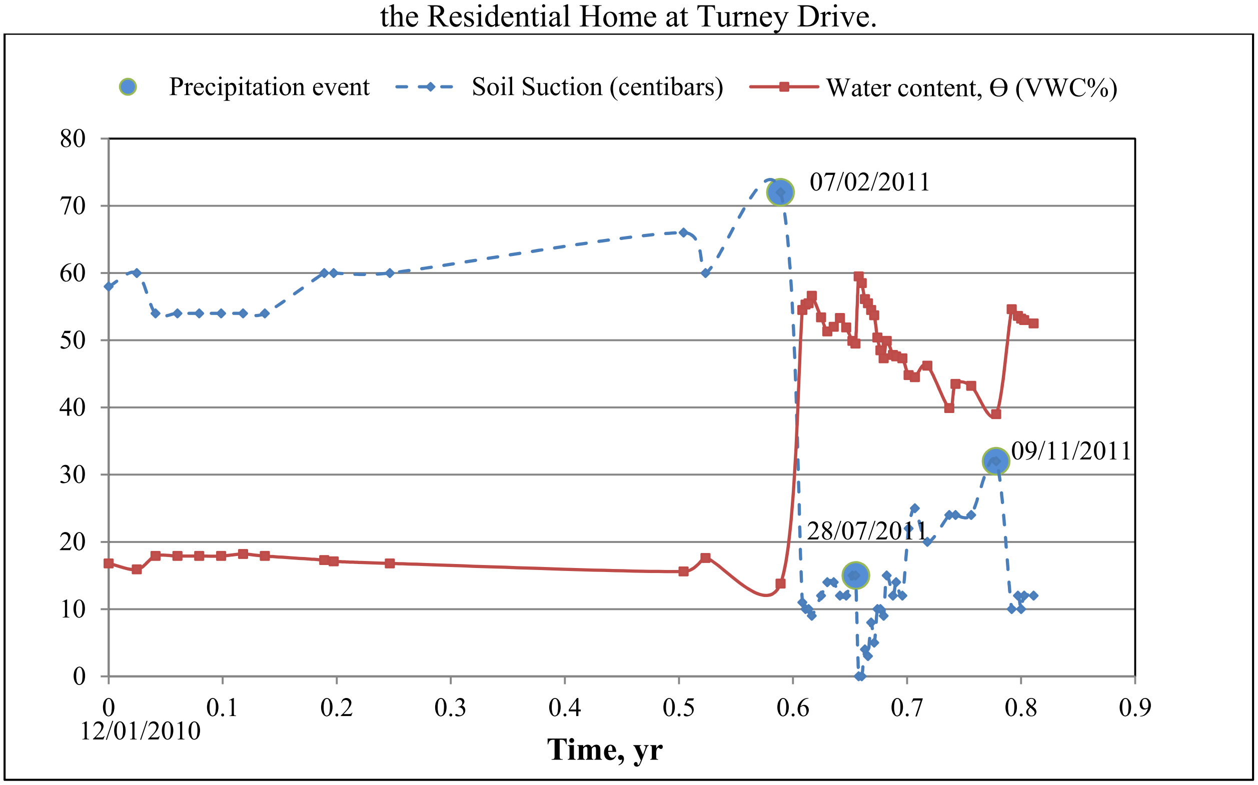

Figure 4.10: The Measured Water Content and Soil Suction at Station A2 Located at SW Corner of the Residential Home at Turney Drive.

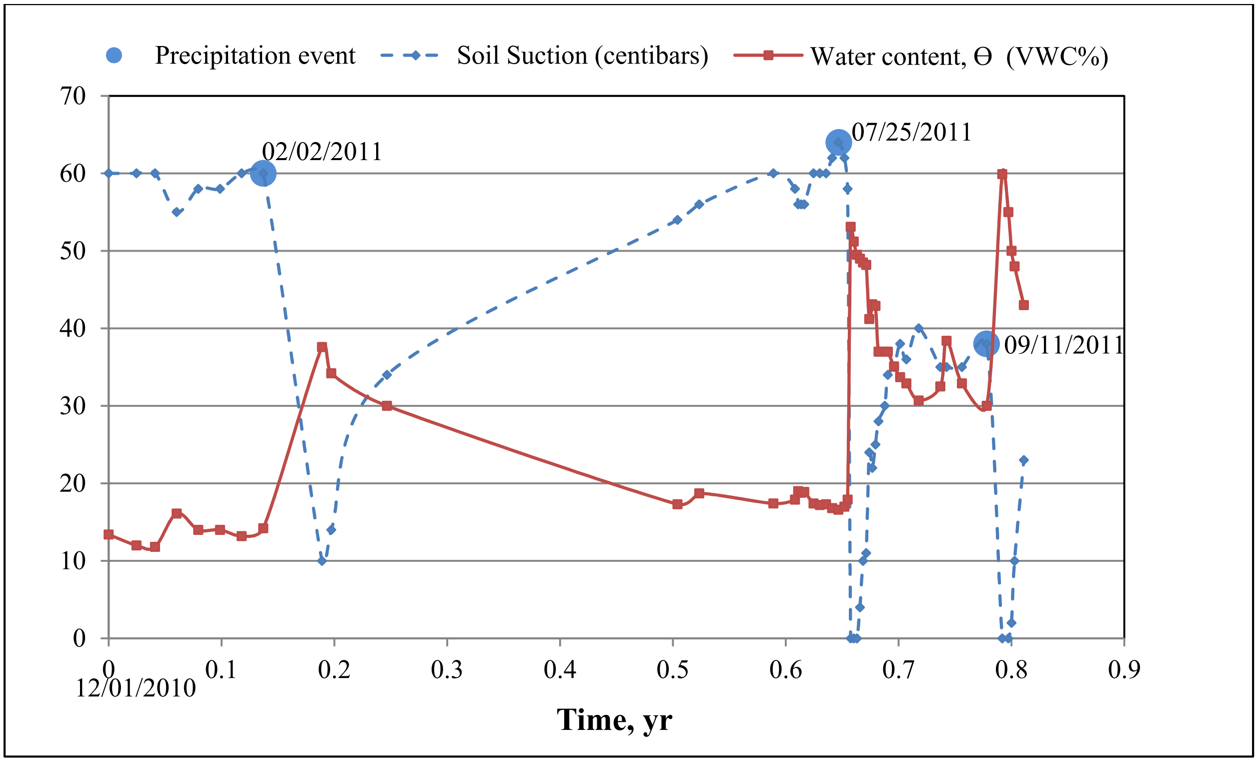

Figure 4.11: The Measured Water Content and Soil Suction at Station A3 Located at NW Corner of the residential home at Turney Drive.

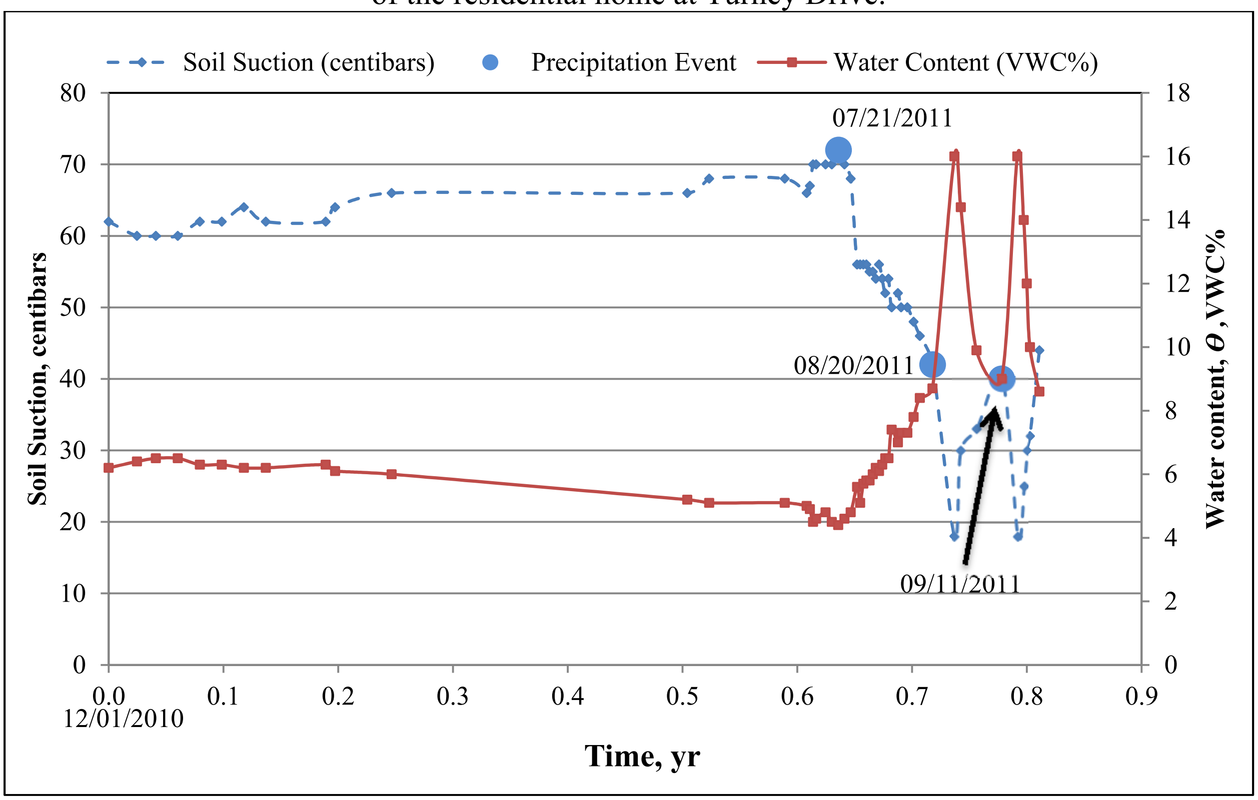

Figure 4.12: The Measured Water Content and Soil Suction at Station B1 at Desert Location near to El Paso.

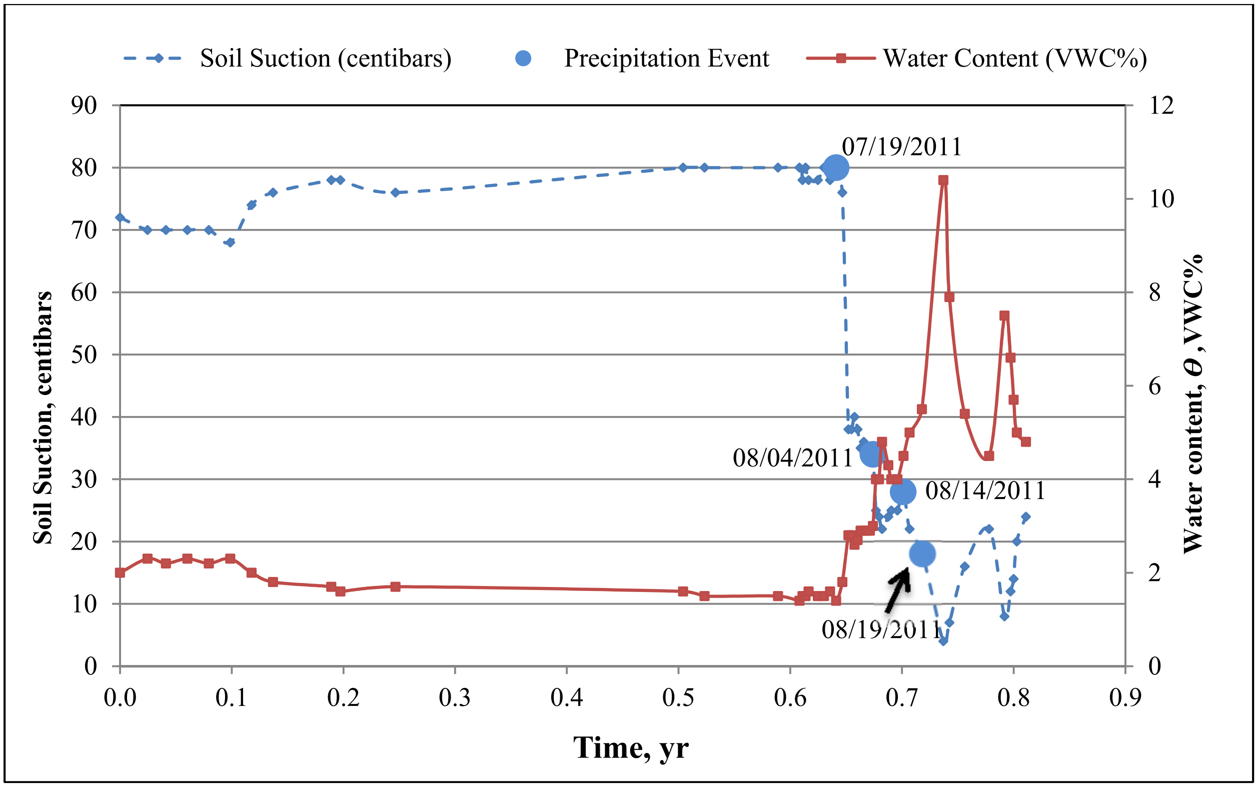

Figure 4.13: The Measured Water Content and Soil Suction at Station B2 at Desert Location near to El Paso.

5. Summary, Conclusions and Recommendations

5.1 Summary

This thesis provides an alternative solution to the conventional stormwater management approaches. A design for Low Impact Development (LID) practices was adapted to the Desert Southwest conditions. LID is a relatively new technique that can naturally store, infiltrate, evaporate, retain, and detain runoff. A series of LID practices can form an Integrated Management Practices (IMP) system. IMP system depends on breaking the watersheds to mini drainage areas and capturing the stormwater in small-scale practices located on each drainage area instead of large, costly pond structures located at the downstream end of the watersheds. This system can treat the environmental and private property damages resulting from the change in the hydrology of a region, due to the expansive urbanization and the conversion of the surface cover from permeable desert to impermeable surfaces such as roofs and pavements. The damages from traditional development may include: 1) groundwater recharge reduction, 2) increase in peak and total discharge, 3) flooding generation that threatens people, wildlife, and property. An IMP system was designed in this study for a single family residential lot as a sample of developed areas. The design can be applied for larger areas, such as residential subdivision, by following the same principles. Twenty years of historical weather data, including temperature and precipitation, was used for the design. In addition, the design was applied for three large cities in the Southwest, including El Paso, TX, Albuquerque, NM, and Phoenix, AZ, in order to see the differences in the results when the circumstances differ. The model lot was subdivided to mini watersheds with two options of the runoff capture area: 1) the residential lot and 2) the residential lot with the half of the adjacent street. The design aims to keep the hydrology of the study area as it was not developed. The runoff that will be generated by the impermeable

surfaces will be captured and detained in small-scale bioretention units and allowed to soak into the subsoil layers. To preserve the hydrology of the area, the entire discharge will not be captured, only the amount that exceeds the discharge that would be generated before the area was developed. What distinguishes the an IMP from a conventional stormwater management system is that IMP consists of small-scale system that mimics natural hydrologic processes by: 1) directing the runoff to natural areas to encourage the growth of native vegetation, 2) increase the infiltration rate into the soil and enhance the groundwater recharge, and 3) prevent runoff from reaching a damaging level to reduce the occurrence of erosion in the watershed.

In addition, the IMP system is more efficient economically than the expensive conventional stormwater management structures. For this study, the system was designed and modified to be as simple as possible where no pipes or subdrains were included. Four LID practices were selected to form a concrete IMP system. The IMP consists of: bioretention units (bioretention cells and vegetation swale) linked by a French drain, and gravel mulch padded with pervious weed barrier. The lawn is generally sloped toward the street, but inside, it is contoured so the runoff is directed toward the bioretention units. Each unit is gently sloped, so when flooded the excessive water will be transmitted by the French drain to the next unit. The last unit is linked to the adjacent street, so if all of the lawn is flooded the water will be moved to the street to be captured by the domestic drainage system. The overflow would not happen unless a larger storm than the ones occurred in the last twenty years is encountered.

The runoff captured by the LID practices and stored in the soil below the bioretention units was used to design an efficient passive landscape for the sample house. The passive landscape design was conduct where the need to irrigate the landscape would be eliminated after root establishment. Native trees and shrubs with low water requirements were selected for the

designed landscape. They can be grown in and around the bioretention LID practices. Different options of tree-shrub mixture were examined to see the difference in the size of green area that can be passively grown. Grasses were excluded from the design because of their high water requirements and the shallow root system. However, if a turf area is desired, it can be grown using a different irrigation system. For a comparison purpose, a differential cost analysis between the conventional landscape and the passive landscape was conducted.

Another study was conducted for this thesis. It is an examination of the change in soil water energy by measuring the soil water content and soil suction at two different locations with different properties in El Pas, TX for 10 months at a same soil depth. One of the sites is a single residential home that is located in an urban area and has a simple landscape with some LID practices. Three measurement stations were installed at the lawn area of this house in three different positions. The other location is at a desert near to El Paso. Two other measurement stations were installed in there. The porous of this study is to see the change in the energy of the soil water and compare it between the two sites.

5.2 Conclusions and recommendations

The findings in this thesis can be summarized in four categories: 1) the area size of the LID practices (bioretention units) comparing to the size of capture area (impermeable area) in the three cities, 2) the size of the passive landscape in the three cities, 3) differential cost, and 4) the change in water moisture energy in the different measurement stations.

The size of the bioretention area that is needed to capture the excessive amount of runoff over the amount generated when the area is not developed is:

1. 24% of the size of the impermeable area in El Paso.

2. 22% of the size of the impermeable area in Albuquerque.
3. 22% of the size of the impermeable area in Phoenix.

These ratios are for capturing the amount of runoff that exceeds the amount of the area as it is not developed. The purpose of the design is to keep the hydrologic characteristics of the region as same as the ones existing before the area is disturbed and developed. However, the size of the bioretention units can be larger if more or all of the runoff wanted to be captured. In addition, other LID practices, than the ones used in tis studies can be tried with the different development components.

The results of the landscape design show that a considerable size of a green area that consists of native shrubs and trees can irrigated by the water captured in the LID bioretention units throughout the year once their roots have completely established. The size of the green area differs based on the number of trees and the number of the shrubs that is desired to be grown. Since trees have higher water requirements (evapotranspiration rate) than shrubs do, lower crown area of trees can be grown under the same conditions. When the half of the adjacent street was considered in the second option of the capture area, more runoff was found to be captured in a larger bioretention unit. This extra amount of captured water increased the size of the passive green area in the lot. Capturing 100% of precipitation increases the plant crown area by amount of 10%. Therefore, if more green areas are desired, larger amount of runoff than the amount that exceeds the pre-development runoff can be captured regardless the change in the hydrologic properties. The ratios of the crown green area to the total residential lot for the two capture area options (lot and lot + street) in the three representative cities are shown in the figure (5.1). Approximately, 20%-50% of the lot area can be covered by trees and shrubs with no need for watering subsequent to root establishment.

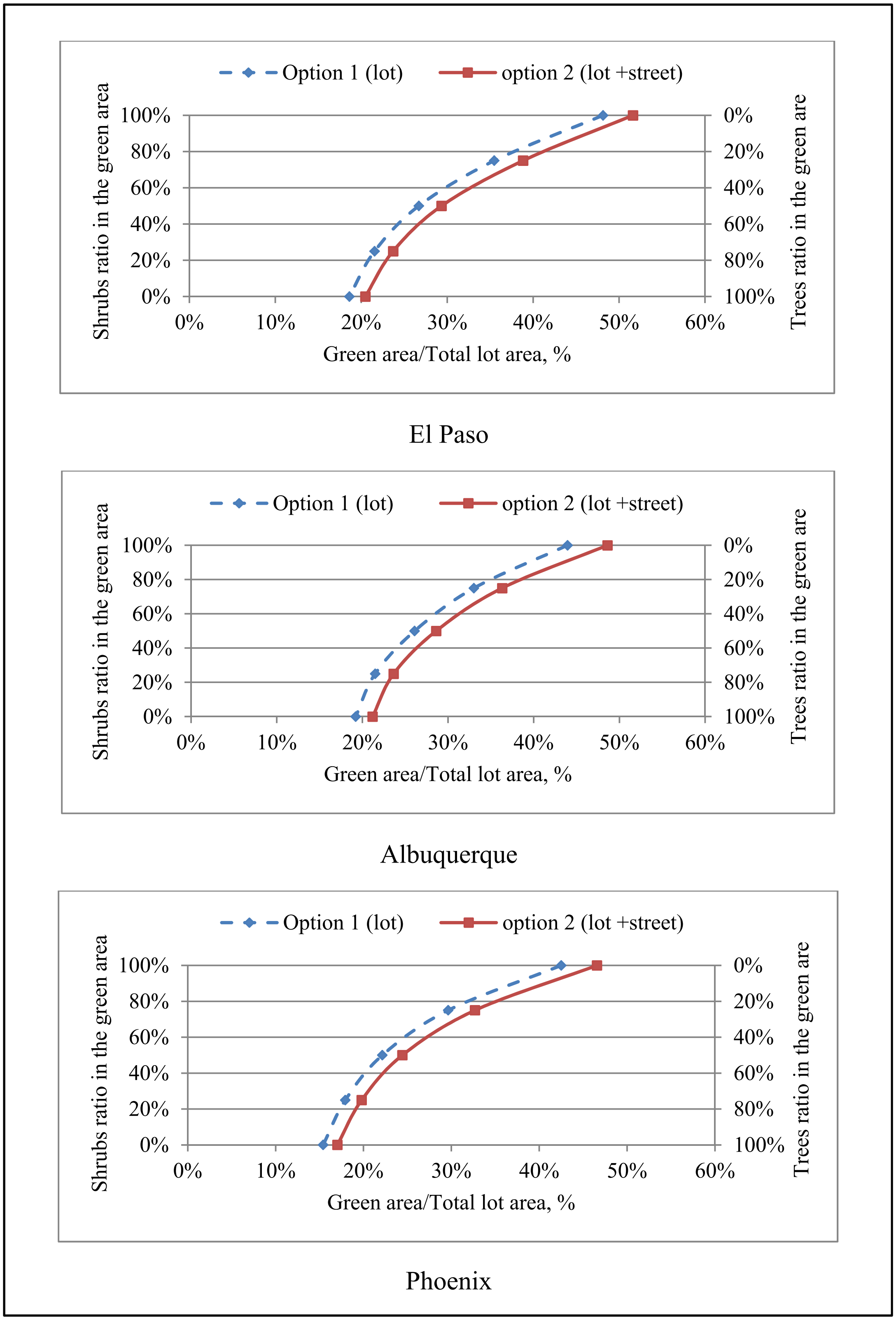

Figure 5.1: The Ratio of the Green Crown Area to the Total Lot Area Based on the Ratio of Trees and Shrubs in the Green Area for the Two Options of the Capture Area in: a) El Paso, b) Albuquerque, and c) Phoenix.

The values that were used for the plants' water requirements (evapotranspiration rates) are collected from deferent federal agencies and universities across the United States. Evapotranspiration rate (ET) is a highly variable and changeable parameter. It differs from vegetation species to another and from location to another for the same species. It is mostly estimated for fully irrigated plants. Therefore, it is decidedly recommended for future studies to measure the actual evapotranspiration rates for the native plants that are passively grown because their ET may be lower than the irrigated plants thus larger green areas can be obtained. Moreover, other vegetation species can be tried to see how the size of the passive landscape changes with different plant water requirements.

The findings of the differential cost analysis between the conventional landscape and the passive landscape show different amount of savings between the representative cities because of the difference in the water rate. The results show that about 70% of the original cost of the conventional landscape can be saved over 10 years if the passive landscape is implemented instead of it, and about 50% of the annualized cost can be saved in the three cities.

The IMP system and the passive landscape were designed for three large cities in the Desert Southwest region. They represent the developing cities in the region were stormwater management problems are more likely to happen. However, for future studies the design can be adapted to other cities in this region or in another region with different climate, geology and topography circumstances. The designed landscape is totally passive and the selected plants have low water requirement. Prospectively, other options can be studied. For example, plants with higher water requirements can be included and the system can be designed to be semi-passive where plants should be irrigated at certain times during the year to fulfil their water needs.

The findings of the soil moisture study can be summarized in the following points:

- The relationship between the soil water content and the soil suction is inverse one.
- When the soil water content is low (dry soil) the value of the soil suction increases.

- When large storm occurs, the soil gets saturated and water content reaches the highest level and the soil suction dramatically decreases to zero.
- After the rain stops, the water drains out and the water content decreases and the soil suction increases.
- The water content and the soil suction values change quickly after the saturation and then the rate of changing becomes slower.
- that the change in soil water energy (water content and soil suction) differs from site to another based on:
    1. The location and the properties the site: the soil at three stations that were placed at a single family residence can hold the infiltrated water for longer period of time than the two station in the desert because the surface of the soil at the house is covered by gravel mulch and permeable weed barrier, which reduce the evaporation to the atmosphere.
    2. Soil properties at the measurement station: the soil at the house is amended and prepared to be vegetated and it is more coherent than the desert sandy soil.
    3. The position of the measurement station: Some stations are placed where runoff can arrive to them quicker than the other stations. Therefore, they have better chances to get saturated.

The measurements were collected for 10 months at the same soil depth of about 10 inches under the surface. The same depth has been kept for all of this period of time in order to collect enough data that can give a consistent conception about the change in the water moisture energy. For future studies, the soil depth can be increased to see how the soil water energy changes at deeper subsoil.

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Appendix

Soil Water Content and Soil Suction Measurements

Measure #	Date	Station A1		Station A2		Station A3		Station B1		Station B2	
		TDR	SS	TDR	SS	TDR	SS	TDR	SS	TDR	SS
1	12/1/2010	12.0	60.0	16.8	58.0	13.4	60.0	6.2	62.0	2.0	72.0
2	12/10/2010	11.2	62.0	15.9	60.0	12.0	60.0	6.4	60.0	2.3	70.0
3	12/16/2010	12.0	60.0	17.9	54.0	11.8	60.0	6.5	60.0	2.2	70.0
4	12/23/2010	14.3	58.0	17.9	54.0	16.1	55.0	6.5	60.0	2.3	70.0
5	12/30/2010	13.3	60.0	17.9	54.0	14.0	58.0	6.3	62.0	2.2	70.0
6	1/6/2011	13.0	60.0	17.9	54.0	14.0	58.0	6.3	62.0	2.3	68.0
7	1/13/2011	13.3	60.0	18.2	54.0	13.2	60.0	6.2	64.0	2.0	74.0
8	1/20/2011	14.5	58.0	17.9	54.0	14.2	60.0	6.2	62.0	1.8	76.0
9	2/8/2011	14.0	60.0	17.3	60.0	37.6	10.0	6.3	62.0	1.7	78.0
10	2/11/2011	14.2	60.0	17.1	60.0	34.2	14.0	6.1	64.0	1.6	78.0
11	3/1/2011	15.6	60.0	16.8	60.0	30.0	34.0	6.0	66.0	1.7	76.0
12	6/3/2011	17.2	60.0	15.6	66.0	17.3	54.0	5.2	66.0	1.6	80.0
13	6/10/2011	18.2	56.0	17.6	60.0	18.7	56.0	5.1	68.0	1.5	80.0
14	7/4/2011	17.9	60.0	13.8	72.0	17.4	60.0	5.1	68.0	1.5	80.0
15	7/11/2011	14.5	72.0	54.5	11.0	17.9	58.0	5.0	66.0	1.4	80.0
16	7/12/2011	14.6	72.0	55.3	10.0	19.0	56.0	4.9	67.0	1.5	78.0
17	7/13/2011	15.0	70.0	55.5	10.0	18.8	56.0	4.5	70.0	1.5	80.0
18	7/14/2011	17.0	64.0	56.6	9.0	18.9	56.0	4.6	70.0	1.6	78.0
19	7/17/2011	16.9	64.0	53.4	12.0	17.4	60.0	4.8	70.0	1.5	78.0
20	7/19/2011	17.0	64.0	51.3	14.0	17.2	60.0	4.5	70.0	1.5	80.0
21	7/21/2011	17.1	64.0	52.0	14.0	17.3	60.0	4.4	72.0	1.6	78.0
22	7/23/2011	17.1	64.0	53.3	12.0	16.8	62.0	4.6	70.0	1.4	80.0
23	7/25/2011	17.3	57.0	51.9	12.0	16.6	64.0	4.8	68.0	1.8	76.0
24	7/27/2011	18.9	56.0	49.9	15.0	17.0	62.0	5.6	56.0	2.8	38.0
25	7/28/2011	18.7	55.0	49.5	15.0	17.9	58.0	5.1	56.0	2.8	38.0
26	7/29/2011	57.7	0.0	59.5	0.0	53.1	0.0	5.7	56.0	2.6	40.0
27	7/30/2011	55.0	0.0	58.5	0.0	51.2	0.0	5.8	56.0	2.7	38.0
28	7/31/2011	53.5	4.0	56.1	4.0	49.5	0.0	5.8	55.0	2.9	35.0
29	8/1/2011	52.0	2.0	55.5	3.0	49.0	4.0	6.0	55.0	2.9	36.0
30	8/2/2011	52.0	3.0	54.5	8.0	48.5	10.0	6.2	54.0	2.9	35.0
31	8/3/2011	53.6	6.0	53.7	5.0	48.2	11.0	6.1	56.0	2.9	35.0
32	8/4/2011	48.5	13.0	50.4	10.0	41.2	24.0	6.3	54.0	3.0	34.0
33	8/5/2011	48.4	14.0	48.5	10.0	43.1	22.0	6.5	52.0	4.0	25.0
34	8/6/2011	48.1	15.0	47.3	9.0	42.9	25.0	6.5	54.0	4.0	24.0
35	8/7/2011	49.5	23.0	49.9	15.0	37.0	28.0	7.4	50.0	4.8	22.0
36	8/9/2011	49.8	20.0	47.8	12.0	37.0	30.0	7.0	52.0	4.3	24.0
37	8/10/2011	50.2	18.0	47.6	14.0	37.0	34.0	7.3	50.0	4.0	25.0
38	8/12/2011	47.9	24.0	47.3	12.0	35.1	35.0	7.3	50.0	4.0	25.0

39	8/14/2011	44.8	34.0	44.8	22.0	33.7	38.0	7.8	48.0	4.5	28.0
		Station A1									
Measure #	Date	TDR	SS	TDR	SS	TDR	SS	TDR	SS	TDR	SS
41	8/20/2011	43.2	35.0	46.2	20.0	30.7	40.0	8.7	42.0	5.5	18.0
42	8/27/2011	39.4	38.0	39.9	24.0	32.5	35.0	16.0	18.0	10.4	4.0
43	8/29/2011	38.4	38.0	43.5	24.0	38.4	35.0	14.4	30.0	7.9	7.0
44	9/3/2011	39.3	38.0	43.2	24.0	32.9	35.0	9.9	33.0	5.4	16.0
45	9/11/2011	33.0	45.0	39.0	32.0	30.0	38.0	9.0	40.0	4.5	22.0
46	9/16/2011	30.7	52.0	54.6	10.0	59.9	0.0	16.0	18.0	7.5	8.0
47	9/18/2011	32.0	46.0	53.6	12.0	55.0	0.0	14.0	25.0	6.6	12.0
48	9/19/2011	33.0	45.0	53.2	10.0	50.0	2.0	12.0	30.0	5.7	14.0
49	9/20/2011	37.0	42.0	53.0	12.0	48.0	10.0	10.0	32.0	5.0	20.0
50	9/23/2011	39.0	40.0	52.5	12.0	43.0	23.0	8.6	44.0	4.8	24.0

Vita

Abubaker Ali Alamailes was born on July, 10th, 1983 in Misurata, Libya, the first son of Ali A. and Afia A. and graduated from Al-Geeran High School, Misurata, Libya. After the completion of his undergraduate degree from the University of Misurata in Civil Engineering, Abubaker began his graduate studies in Civil Engineering in August of 2007 at the University of Misurata. Whilst pursuing his graduate degree, Abubaker worked as a teacher assistant for the Civil Engineering Department at the same university. During the first months of his graduate studies, Abubaker received glad tidings that he had been qualified for a scholarship to get his master's degree abroad. Abubaker selected the United State of America to accomplish his graduate studies. After learning English for a year at Portland State University, Abubaker was accepted in the Department of Civil Engineering at the University of Texas at El Paso.