SUSTAINABLE HOUSE-SCALE PASSIVE RAINWATER CAPTURE LANDSCAPE IN THE DESERT SOUTHWEST

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ABSTRACT

A passive rainwater harvesting technique was used to design a sustainable landscape for a residential lot located in the desert. The design was adapted to the Desert Southwest region of the United States based on thirty years of daily historical climate data including precipitation and reference evapotranspiration (ET_0). Four cities including El Paso, TX, Albuquerque, NM, Phoenix, AZ, and Pahrump, NV, were selected to represent the area. The residential lot was broken up into micro-watersheds reflecting the runoff of water from each separate portion of the house roof, driveway, and lawn area. The paper explains in detail the design steps for one of the micro-watersheds where water retention and infiltration structures were distributed throughout the soil area to capture stormwater runoff close to its source. A passive rainwater capture landscape was obtained by using the stormwater captured in the infiltration structures and stored in the surrounding soil. Native vegetation (shrubs and trees) will use this water exclusively for growth. These plants will not require watering once their root establishment period has passed, except in extreme droughts. Meanwhile, stormwater discharge from the lot will decrease and the groundwater recharge will increase. Results indicate that the current urban water budget can be made sustainable by replacing watering of landscape by municipal water with harvested stormwater. This results in a relatively lush and shady environment even in desert climates. The success is an artifact of the tendency of urban watersheds to increase the volume of stormwater relative to pre-development conditions.

KEYWORDS

stormwater harvesting, micro-watershed, sustainable use, evapotranspiration, infiltration trenches

INTRODUCTION

The urban water budget in arid and semi-arid regions is changing rapidly in response to population growth, over pumping of groundwater, and over allocation of surface water. The challenge for sustainable water supply in arid and semi-arid regions is to close the loop by direct reuse of all waters entering sewage treatment plants (Figure 1). This works well except for the

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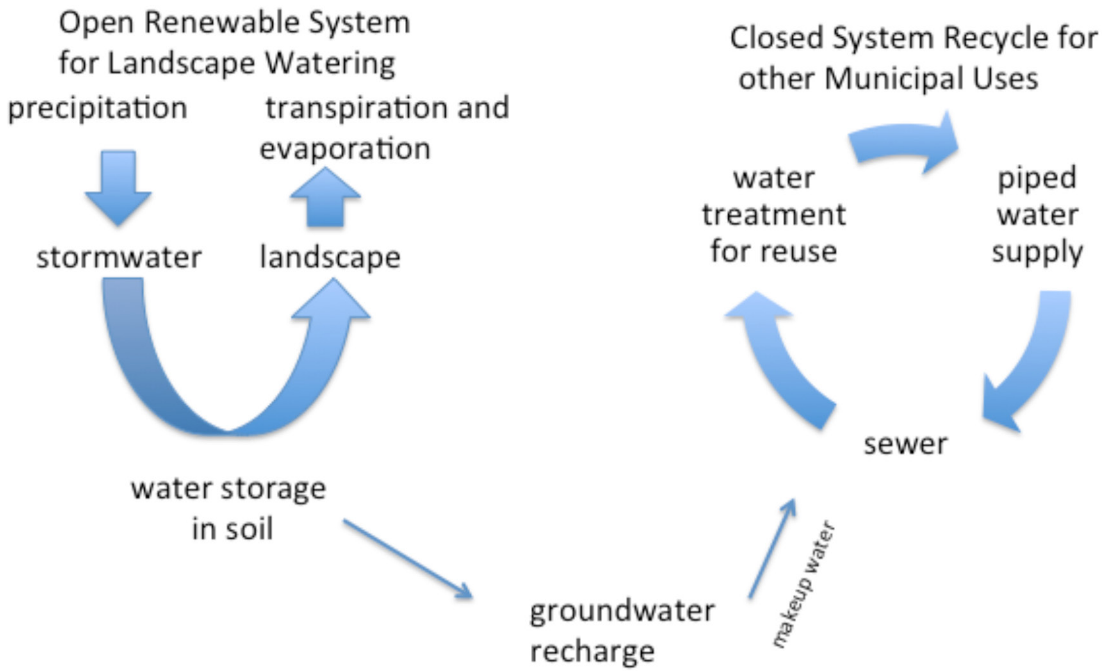
FIGURE 1. Sustainable concept of the urban water budget in arid and semi-arid regions, this paper addresses the open portion of the water budget.

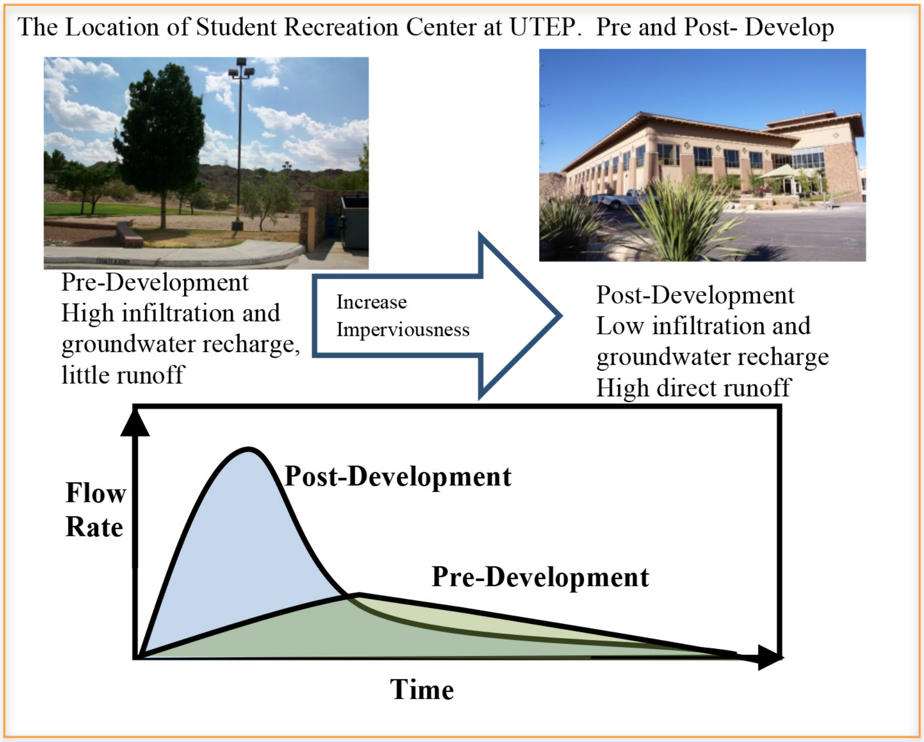


approximately one third of water that is used for landscape watering. Landscape water predominantly exits the urban watershed through evaporation and transpiration and does not go down a sewer that would allow it to be reused within the context of the urban water system. In the United States, conversion of rural areas with pervious surfaces into urban landscapes with impervious surfaces has exacerbated the problems associated with the stormwater management (Xiao, McPherson, Simpson, & Ustin, 2007). The increased urban stormwater runoff caused by urbanization can be turned into a resource if it is used to replace municipal water that is currently used for landscape watering. This is the argument for stormwater harvesting.

Passive stormwater harvesting, which benefits from the enhanced urban runoff, is adequate to provide a lush urban landscape that does not require additional watering, once landscape vegetation roots have been established. The goals of the work described here are to demonstrate that lush residential urban landscape can be watered solely with stormwater captured on the lot, as well as to illustrate water balance and storage techniques appropriate for applying passive stormwater harvesting in urban areas in the southwestern US.

The changes related to uncontrolled development increase the peak and total discharges while reducing infiltration rates (Figure 2). These elements are associated with increased risk of flash flooding. Groundwater recharge may also 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, Ransel, Todd, & 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, enough to serve the needs of up to 1.5 million people per year when considering an average household (Otto, Ransel, Todd, & et. al., 2002).

FIGURE 2. Stormwater runoff response to urban development.

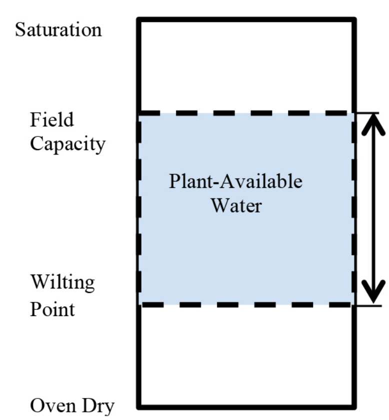


This paper proposes a technique to create a passive rainwater landscape that reduces the environmental impacts of new and/or existing developments. Desert climates have different demands for hydraulic management compared to more humid climates that serve as the basis for most Low Impact Development (LID) guidelines. LID is a site level stormwater management design approach with an objective of maintaining the hydrologic cycle or meeting targeted watershed and the National Pollutant Discharge Elimination System (NPDES) objectives. Primarily, water scarcity and long dry periods between precipitation events dictates that water storage for use in landscape watering is of more importance than water treatment and delayed release. In this design, the landscape survives on the available moisture, or water content in the soil.

Field capacity is the water content (θ_{FC}) remaining in the soil after 48–72 hours of gravitational drainage, after the soil has been saturated by a significant irrigation or precipitation event. The wilting point (θ_{WP}) is the water content in the soil at which the plant reaches its wilting condition.

Reasonably accurate estimates of field capacity and permanent wilting point can be obtained simply by knowing the texture of the soils. Table (1) shows the estimates published by Saxton and Rawls (2006) as a starting point for plant available water estimation. Soil properties

FIGURE 3. Soil storage of plant available water.



enhancement (e.g., adding organic matter) could also be used to increase the amount of vegetation per unit area.The water storage capacity of the soil can be obtained by,

$$C = (\theta_{FC} - \theta_{WP})\, d_r \tag{1}$$

Where:

- C: existing available water storage in the soil (in)
- θ_{FC}: soil field capacity
- θ_{WP}: soil wilting point, and
- d_r: root depth (in)

The root depth (d_r) of the plants selected for the landscape vegetation is an important factor in the determination of the storage capacity of the system as the plants cannot take-up water below this depth. Robert P. Gibbens and James M. Lenz conducted a study in 2001 about the root systems of some Chihuahuan Desert plants. They found that most of shrubs have root system depths of 2 meters (6.5 ft) or more, while trees have a deeper root system up to 3 meters (10 ft). Gibbens and Lenz (2001) also found out that tree root systems are wider than shrub roots. In passive rainwater harvesting systems the established root depth of the landscape vegetation determines the water storage capacity of the system and this is in contrast with LID systems.

Rain barrels and other tanks, commonly presented in LID are, in general, too expensive for watering the overall landscape in arid and semi-arid climates. The infrequent and seasonal nature of rainfall, would require large tanks to store stormwater runoff from the monsoon season in order to meet the annual demand. Instead, we propose systems where rainwater is stored in the subsurface as soil moisture making it accessible to landscape vegetation roots. The volume storage for the soil "tank" is:

$$V_T = A_s\, d_r\, (\theta_{FC} - \theta_{WP}) \tag{2}$$

- V_T: tank volume
- A_s: soil area (total permeable yard area), and

As an example, using the house model from Figure 9 and its location in El Paso, we can apply the a soil area of 2,160 ft^2, a 12-ft root depth, and values of 0.27 and 0.17 for the field capacity and wilting point, respectively, as obtained from Table 1. These values would yield a tank volume of 2,600 ft^3 (~19,400 Gal) which could cost ~$20,000, a prohibitive price in a modestly priced suburban home relative to using the soil in the yard for water storage (free).

TABLE 1. Estimates of Field Capacity and Wilting Point (Saxton and Rawls, 2006).

Texture	FC (%)	WP (%)
Sand	10	5
Loamy sand	12	5
Sandy loam	18	8
Sandy clay loam	27	17
Loam	27	14
Sandy clay	36	25
Silt Loam	31	11
Silt	30	6
Clay loam	36	22
Silty clay loam	38	22
Silty clay	41	27
Clay	42	30

The method proposed here is an enhancement of the natural way desert plants survive. The primary benefit is the elimination of landscape watering, the main non-recyclable use of municipal water in arid urban localities, through the use of water stored in the soil to grow native drought tolerant landscape vegetation. Secondary benefits include the reduction of stormwater runoff and increased lush landscape vegetation.

PASSIVE RAINWATER CAPTURE LANDSCAPE MODELLING

The main objective of this system is to route the stormwater runoff from a development's surface to a variety of small rainwater capture features. A rainwater capture feature is an in-soil depression optionally filled with porous backfill (e.g., size sorted gravel) that has an appropriate volume to store the runoff form the design storm. Water in the depressions infiltrates into surrounding soils where it is stored as soil moisture.

Rainwater capture features can take many shapes including bioretention basins, dry wells, filter strips, vegetated buffers, swales, infiltration trenches ("French drains"), and/or gravel cover over soil. The rainwater capture features chosen for this paper are infiltration trenches modelled after French drains. Infiltration trenches are small scale trenches that are filled with size sorted gravel and designed to encourage fast stormwater infiltration through the sides, bottom and end of the trench. The trenches are employed to receive hold or convey stormwater runoff from watershed areas that are relatively free of sediments like parking lots, roofs, sidewalks, or areas stabilized with plants. As with other rainwater capture structures, infiltration trenches should be placed at least 10 feet away from building foundations as stated in the 2000 International Building Code (IBC) Section 1803.3 (International Code Council, 2000) to avoid saturating the soil near the building foundation. The area between the infiltration trenches should be planted with native species that have low water requirement and wide deep root systems. The surface of the soil is covered by gravel mulch over a permeable weed barrier and sloped to direct runoff toward the infiltration trenches. While the illustrations in this paper are shown in the form of rock filled infiltration trenches, the particular form of the rainwater capture features chosen is unimportant to the water budget and can be chosen based upon aesthetic and practical considerations.

The first step of the water budget design model consists of breaking up the developed lot into micro-watersheds such that each corresponds to the stormwater runoff from a separate portion of a building roof, lot, parking lot, sidewalk, or driveway. Each micro-watershed is modeled as rainwater capture areas with surface properties modeled using the Natural Resources Conservation Service (NRCS) method. Infiltration trenches, soil properties, and associated plant growth areas are then sized for each individual micro-watershed.

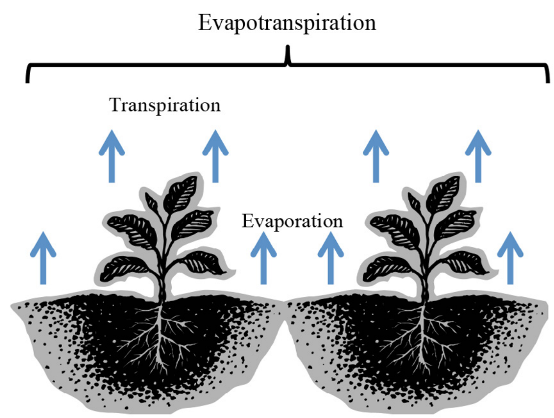
Stormwater runoff is diverted into the rainwater capture features that temporarily store all the stormwater up to the design basis storm, and then gradually infiltrate the water into the surrounding soils. The adjacent soils store the water using the concepts of unsaturated flow and soil moisture holding capacity. Excess stormwater that cannot be held temporarily in the rainwater capture features is assumed to exit to the street and generate stormwater runoff. The landscape vegetation uses water from the moisture stored in the soil. The captured water above the field capacity of the surrounding soils drains downward to recharge groundwater. The numerical model is used to balance historical climate, stormwater runoff capture area, temporary water storage capacity, soil long term water storage, and daily landscape vegetation water use.

The model was developed to easily be adapted by any user to optimize the passive rainwater harvesting system's design to their particular requirements. The model consists of two interconnected Microsoft Excel spreadsheets where the first (BV) is used to determine the stormwater temporary storage volume required in the available soil area for each micro-watershed. The spreadsheets use iterative calculations and manual input to provide multiple solutions from which the user can make a selection. For illustration purposes, a one-inch 24-hour storm was used for the results shown in this paper as the design storm. The design storm can be varied to conform to local goals and/or regulations for stormwater control as desired by the user. A storm greater than the design size will cause some runoff to exit the system as stormwater. The second sheet (WB) contains a water balance simulation to estimate: the area of the passive landscape that can be obtained based on the size of the capture features determined in the BV sheet; the climate conditions (precipitation and reference evapotranspiration, ET_0); the type of vegetation grown; and the soil characteristics. The BV sheet uses thirty years of daily site specific historical precipitation and reference evapotranspiration data, obtained from Utah State University Climate Center (Utah State University), with the water balance performed on a daily time step.

Statistical Analysis for Historical Precipitation and Reference Evapotranspiration Data

The thirty year historical data was used for the passive landscape water balance simulations. Evapotranspiration (*ET*) corresponds to water loss from both, evaporation to the atmosphere from the soil surface, and transpiration from the plants growing thereon (Figure 4).

FIGURE 4. Evapotranspiration Process.



All simulations presented in this work are based upon daily climate and weather data; however, climatic summaries provide useful insight for comparison between cities. The average monthly precipitation and evapotranspiration over the thirty years is shown on Figures 5 and 6, respectively. From Figure 5 it can also be observed that El Paso, TX and Albuquerque, NM have higher average precipitation than Pahrump, NV (near Las Vegas) and Phoenix, AZ with El Paso and Albuquerque demonstrating higher precipitation in the summer (monsoon) months. Phoenix presents higher precipitation in July and August, yet appears relatively constant between the months of December through March, whereas Pahrump demonstrates higher precipitation in the winter months. While all four cities follow a similar trend, Albuquerque has the lowest average reference evapotranspiration, as can be seen on Figure 6.

Capture Feature Size Determination

The infiltration trenches used as capture features in this example have to meet two basic requirements: a) adequately large to capture the design rainfall after the losses of both infiltration into the soil and evapotranspiration to the atmosphere, and; b) smaller than the size of the available soil area.Infiltration trench storage volume is taken as:

$$V_a = A_b \, \varphi \, d_b \tag{3}$$

FIGURE 5. Average monthly precipitation summary.

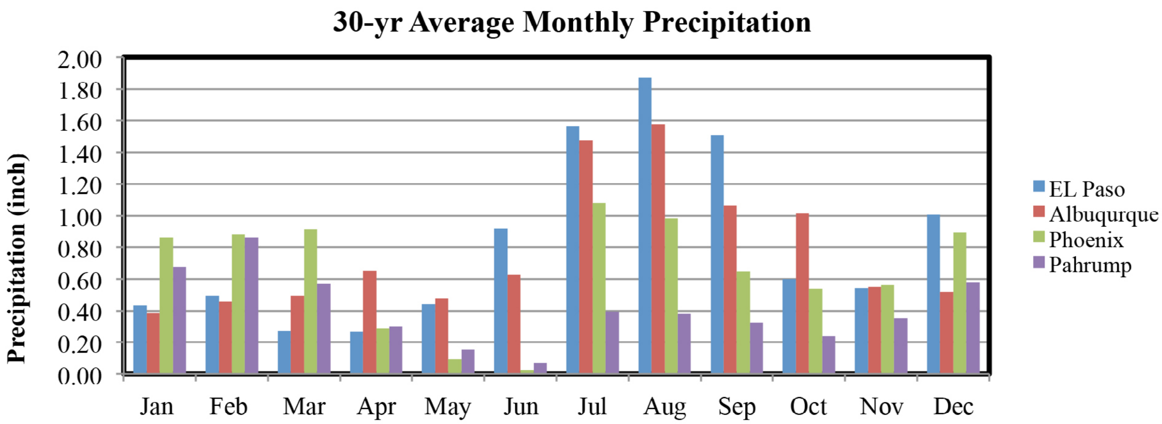
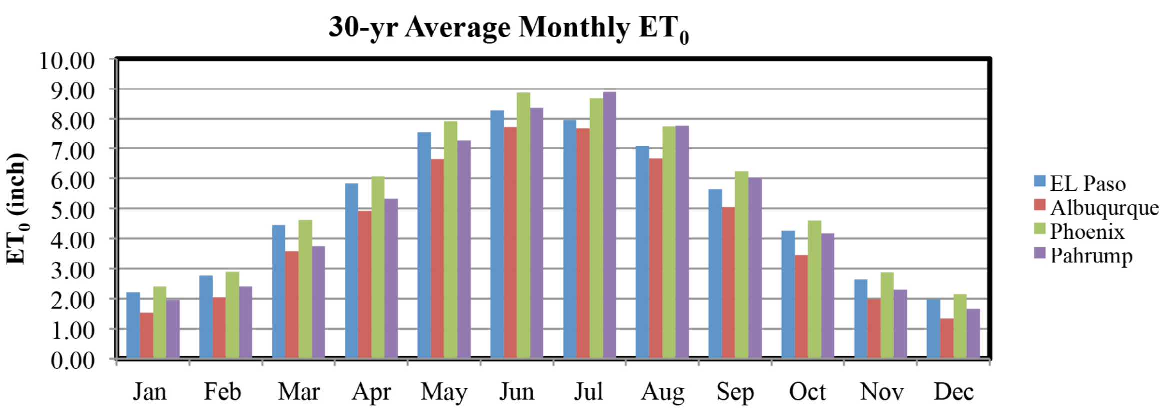


FIGURE 6. Average monthly reference evapotranspiration.



Where,

- V_a: actual infiltration trench volume (ft^3)
- A_b: infiltration trench surface area (ft^2)
- φ: backfill porosity (1 for open shallow depressions), and
- d_b: trench depth (ft)

The required volume of the capture features required for the design storm is:

$$V_r = (P\,A_w) - (I\,A_s) - (E\,A_w) \tag{4}$$

Where,

- V_r: required infiltration trench volume (ft^3)
- P: precipitation (design storm) (ft)
- A_w: area of micro-watershed (ft^2)
- I: infiltration into soil during storm (ft), and
- E: evaporation during storm (ft)

Initial infiltration into the soil area during any storm (I) is taken as the difference between runoff at the impermeable surface condition and runoff at the permeable condition over the soil area; this assumes that the water loss from the impermeable surface predominantly represents evaporative losses. Infiltration is calculated as:

$$I = (R_i - R_p)A_s \tag{5}$$

Where,

R_i: runoff at impermeable conditions (Eq. 7 with CN=98) (ft)

R_p: runoff at permeable conditions (Eq. 7 with CN=75) (ft)

Evaporation (E) is assumed to occur over the entire watershed and it is considered that the NRCS losses from the impermeable surface are mostly evaporation, thus evaporation is estimate by:

$$E = (P - R_i)\,A_w \tag{6}$$

As was formentioned, a one-inch 24-hr design storm is used herein for illustrative purposes, although the methodology described can be used to capture any storm size desired. Designs for larger storms require a larger infiltration trench size (and support more vegetation). The NRCS, formerly SCS, curve number method is used to calculate the volume required for capturing the stormwater generated by the design event (Houghtalen, Osman Akan, & Hwang, 2010). The NRCS method uses the following equation to estimate runoff:

$$R = \frac{(P - I_a)^2}{(P - I_a) + S} \tag{7}$$

Where,

R: stormwater runoff (in)

S: potential maximum retention after runoff begins (in), and

I_a: initial abstraction (in)

Initial abstraction (I_a) is defined as all rainwater losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. Initial abstraction is highly variable but generally is associated with soil and cover parameters, and is found to be approximated by the following empirical equation:

$$I_a = 0.2S \tag{8}$$

S is related to the soil and cover conditions of the watershed through the Curve Number (CN). The value of CN reflects the degree to which land surface conditions will generate runoff. The greater the CN number, the higher the instance of runoff. Information about the soil surface is needed to determine CN for each part of the micro-watershed. For this paper, two surface types were assumed: a) Soil is covered by gravel mulch over a permeable weed barrier (CN = 75), and; b) Impermeable roof /pavement (CN= 98). CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{\text{CN}} - 10$$

Sustainable Landscape Simulation

After obtaining the infiltration trench size, the WB spreadsheet in the model was used to calculate the sustainable landscape area to be passively irrigated by the captured rainwater and the infiltrate to the groundwater. The proposed passive watering is not applicable for high water demand vegetation such as grasses, unless seasonal grasses are planted and allowed to become dormant during drought periods. Optionally, a small amount of artificial watering during the annual dry season allows for even greater amounts of vegetation to be supported.

A relative soil moisture content is defined here to assess the water storage status by the equation:

$$\theta_S = \frac{\theta_A - \theta_{WP}}{\theta_{FC} - \theta_{WP}} \times 100 \tag{10}$$

Where:

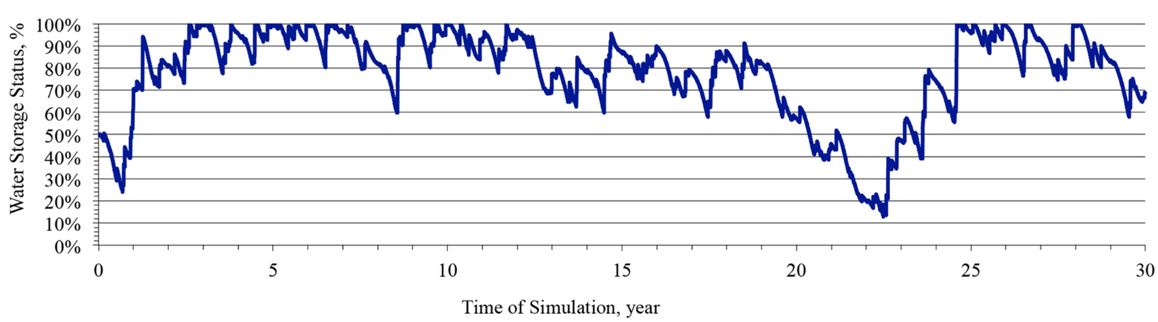
θ_S: soil moisture plant available water (%)

θ_A: actual moisture capacity (%)

The water budget simulation model was built to trace the amount of plant-available water in the soil based on previous 30-year history of the development's region (Figure 7) using daily data and time steps. When the relative soil moisture plant available water (θ_S) reaches 0%, there is no water to support plant growth and plants may die. Most native desert plants (e.g., ocotillo) tend to go dormant rather than die during droughts. The Plant Area/Watershed Area on WB excel sheet should be manually iterated until the amount of landscape vegetation (plant crown area) is supportable without external watering (i.e., relative soil humidity never gets down to zero). For the purpose of illustration, the information from Figure 7 was obtained by using the model house plan in Figure 8 in the El Paso area.

The crown green area was calculated for each location (city) based on its climate condition and soil properties, using the aforementioned daily historical data for the passive rainwater landscape simulation. This simulation is performed by manually iterating the "crown area/watershed capture area" parameter in the BV spreadsheet in order to find the maximum amount of landscape vegetation that can be passively supported, and simultaneously monitoring the graphical change of the relative soil humidity over time (the thirty year domain), as necessary. Should θ_S reach 0% at any point in time, vegetation may die from lack of moisture. In this case the area of vegetation should be reduced and recalculated until a viable fraction of

FIGURE 7. Change in plant available soil moisture storate for the modeled micro watershed (example).



vegetation is reached. If the area of vegetation is small relative to capacity, θ_S will always remain near 100% moisture capacity, meaning more vegetation could be supported. If a smaller value than the maximum area of landscape vegetation is grown in the micro-watershed, then more water from the infiltration trenches will recharge groundwater.

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

$$\Delta C = C + P_N - ET - GW \tag{11}$$

$$P_N = Min[(P - I_s) \times \frac{A_w}{A_s}, V_r/A_s] \tag{12}$$

Where:

- ΔC: daily change in the volume of available water storage in the soil (in)
- P_N: daily net captured precipitation (in)
- I_s: initial abstraction from an impervious surface (used to approximate evaporation) (in)
- ET: daily landscape evapotranspiration (in), and
- GW: daily water assumed to infiltrate to groundwater when field capacity of soil is exceeded (in)

Water storage in the model is the water retained into the soil that is available for vegetative use (Equation 11). This water falls into the range between two volumetric soil water contents (Figure 3): the moist end (field capacity) and the dry end (wilting point).

The net captured precipitation (P_N) is the usable stormwater for the passive harvesting. When the actual precipitation value is larger than the initial abstraction (I_a), the net captured precipitation can be calculated using Equation (7), where P_N is equal to the runoff generated over the micro-watershed. At the same time the calculated value must be smaller than the sum of both, the calculated infiltration trench capacity and the infiltration into the soil over the micro-watershed area.

Many methods have been used to estimate the evapotranspiration rate, mainly empirical equations such as Penman, Priestley-Taylor, Thornthwaite, or Blaney-Criddle. These equations calculate ET using inexpensive and available weather data assuming that vegetation is fully irrigated. In this paper we use the ET_0 values estimated by the National Weather Service and stored with the climatic data. ET_0 is the evapotranspiration corresponding to uniform cover of tall green grass. A plant's rate of evapotranspiration equals the reference evapotranspiration (ET_0) multiplied by the appropriate plant adjustment factor (K_L), as shown in the following equation:

$$ET = K_L ET_0 \tag{13}$$

Where:

- K_L: crop adjustment factor (dimensionless)
- ET_0: reference evapotranspiration (in)

The landscape adjustment factor is a function of several factors including plant type, microclimate, and plant density (Costello et al 1993 and 2000). The average landscape K_L can be calculated by the following equation:

$$K_L = K_s K_{mc} K_d \tag{14}$$

TABLE 2. Adjustment Factor KL for some Established Plant Species. (Goodrich et al. 2000, Pittenger et al. 1990, Pittenger et al. 2001, Shaw and Pittenger 2004, Staats and Klett 1995, and Waterfall 2004).

Common Name	Latin Name	Adjustment Factor (K_L)
Mesquite	*Prosopis glandulosa* (Mesquite)	0.13 to 0.39
Compact Strawberry Tree	*Arbutus unedo* 'Compacta'	0.18 to 0.36
Bearberry	*Arctostaphylos uva-ursi* 'Pacific Mist'	0.18 to 0.36
Workwood	*Artemisia* 'Powis Castle'	0 to 0.36
Twin Peaks Coyote Bush	*Baccharis pilularis* 'Twin Peaks'	0.2
Pink Powder Puff	*Calliandra haematocephala*	0.18 to 0.36
Feathery Cassia	*Cassia artemisiodes* *Cerastium tomentosum*	0 to 0.36 0.25
Orchid Spot Rock Rose	*Cistus x purpureus*	0 to 0.36
White Australian Correa	*Correa alba* 'Ivory Bells'	0.18 to 0.36
Pink Iceplant	*Drosanthemum hispidum*	0.2
Pride of Madeira	*Echium fastuosum*	0 to 0.36
Frades Escallonia	*Escallonia x exoniensis* 'Fradessii' *Ficus microcarpa nitida*	0.18 to 0.36 0.2
Bush Snapdragon	*Galvezia speciosa* *Gazania hybrida*	0 to 0.36 0.25 to 0.50
Trainling Gazania	*Gazania rigens v. leucolaena* 'Yellow Cascade'	0.50 to 0.80
Noelli	*Grevillea* 'Noelli'	0 to 0.36
Needlepoint English Ivy	*Hedera helix* 'Needlepoint'	0.20 to 0.30
Toyon	*Heteromeles arbutifolia*	0 to 0.36
Rose of China	*Hibiscua rosa-sinensis*	0.40 to 0.30
Trainling Lantana	*Lantana montevidensis*	0.18 to 0.36
New Zealand Tea Tree	*Leptospermum scoparium*	0.18 to 0.36
Texas Ranger	*Leucophyllum frutescens* 'Green Cloud'	0 to 0.36
Texas Privet	*Ligustrum japonicum* 'Texanum' *Liquidambar styraciflua*	0.40 to 0.60 0.2
Prostrate Myoporum	*Myoporum* 'Pacificum'	0 to 0.36
Mexican Bamboo	*Otatea acuminata*	0.18 to 0.36
New Zealand Flax	*Phormium tenax*	0.18 to 0.36
Mock Orange	*Pittosporum tobira*	0.18 to 0.36
Spring Cinquefoil	*Potentilla tabernaemontanii*	0.70 to 0.80
Carolina Laurel Cherry	*Prunus caroliniana*	0 to 0.36
Firethorn	*Pyracantha koidzumii* 'Santa Cruz' *Quercus ilex*	0 to 0.36 0.2
Indian Hawthorne	*Rhaphiolepis indica* *Sedum acre*	0.18 to 0.36 0.25
Germander	*Teucrium chamaedrys*	0.18 to 0.36
Periwinkle; Myrtle	*Vinca major*	0.30 to 0.40
Rosemary Bush	*Westringia rosamarinaformis*	0.18 to 0.36
Shiny Xylosma	*Xylosma congestum*	0.18 to 0.36

Where:

K_s: adjustment factor for a particular plant species (dimensionless)

K_{mc}: adjustment factor for shade or microclimate (dimensionless)

K_d: adjustment factor for plant density (dimensionless)

Costello and Jones (1999) classified plant species adjustment factors (K_s) into three general categories, K_s=0.2, 0.5, and 0.9 for low, medium, and high water use landscape, respectively. Costello et al. found in 2000 that plant density factor (K_d) would be equal to one (1) if 70% or more of planted area is covered by trees or 90% of the area is covered by shrubs. K_d may exceed a value of one if the landscape cover has turf in addition to trees and shrubs.

The microclimate factor (K_{mc}) is equivalent to a value of 1 (one) where landscape conditions are similar to reference evapotranspiration conditions (Costello, Mathany, & Clark, 2000). However, it can be increased to the range between 1.1 and 1.4 when sun radiation is reflected from surrounding facilities (e.g., house, road,). Similarly, K_{mc} can be decreased to the range between 0.5 and 0.9 if the plants are in shade and/or protected from wind. Table 2 shows different established crop adjustment factor for different plant species reported by different authors.

Three scenarios were examined in this study with three different values of K_L. The first scenario, where only trees planted, the average K_L value used in the simulation was 30% of ET_0. In the second scenario where the trees were mixed with shrubs to form the green area, the K_L value was 25% of ET_0. In the third scenario included only shrubs with a K_L value of 20% of ET_0.

THE MODEL HOUSE: LOCATION, CONDITIONS, AND MICRO-WATERSHED DELINEATION

In order to generalize the design, the house could be placed at any location in one of the four representative cities. A real house plan was drawn in AutoCAD 2010 (Figure 8) to measure the runoff capture area and all other measurements necessary for the example design and calculations presented herein.

Some conditions are generalized to comply with flexible house locations. For these particular sites in the four cities, the location of the groundwater table is assumed to be deep enough to be ignored. The subsurface conditions were selected based on the dominating soil class in the region presented in soil surveys from the National Cooperative Soil Survey and operated by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS).The site soil conditions are shown in Table 3.

FIGURE 8. Model house plan.

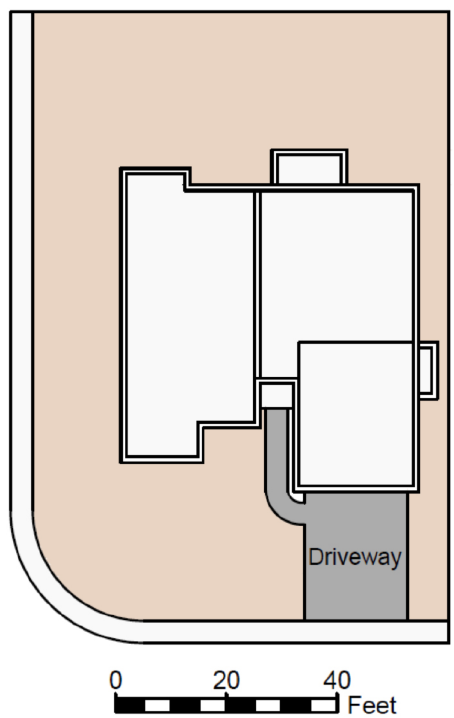
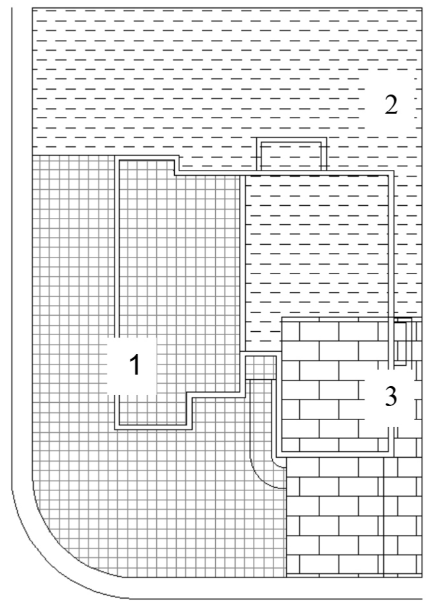


TABLE 3. Site Soil Conditions.

City	Subsurface condition
EL Paso	Sandy clay loam soil
Albuquerque	Loam soil
Phoenix	Silty clay loam soil
Pahrump	Sandy clay loam soil

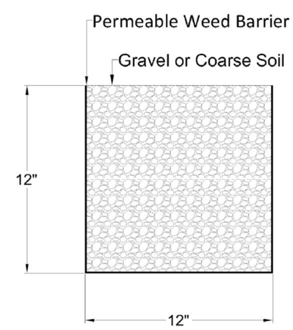
*All surfaces are considered covered with a permeable plastic weed barrier covered by gavel mulch

FIGURE 9. Division of model house into separate micro-watersheds.



For this particular plan, the house was divided into three micro-watersheds shown on Figure 9.The micro-watershed subdivision was made based on the direction of the stormwater that runs off the roofs, driveway, and lawn in the model home. The runoff up to the design storm is be collected and directed to infiltration trenches where it is temporarily stored while infiltrating into the adjacent soil. Each micro-watershed is treated as a separate design problem in the model.

FIGURE 10. Infiltration trench cross section.



INFILTRATION TRENCHES

Infiltration trenches used are assumed to be filled with gravel with a porosity of 35%. Gravel filled infiltration trenches are typically used on flat to moderate slopes, making them suitable for capturing water in flat areas (e.g., house yard) where a level surface is needed, and can be placed perpendicular to the slope.

There are several ways to build infiltration trenches. In this study the trenches were designed to be distributed over the lawn area of the micro-watershed. A typical 1-ft wide by 1-ft deep (1 ft^3/ft) section area was used (Figure 10). The trenches will be surrounded by a perforated weed barrier, as a continuation to the barrier installed beneath the gravel mulch. In order to meet the IBC requirement, infiltration trenches should be connected to an underground pipe, at least 10 feet away from the foundation, to carry the stormwater from the roof (Figure 11).

FIGURE 11. Drain and infiltration trench offset from building.

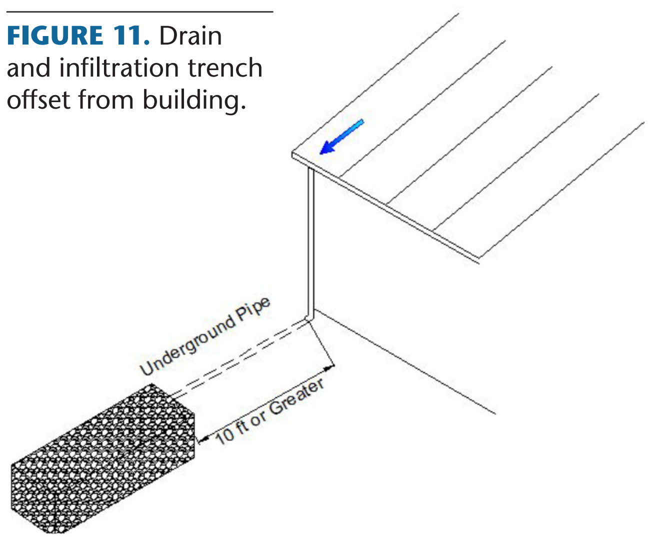
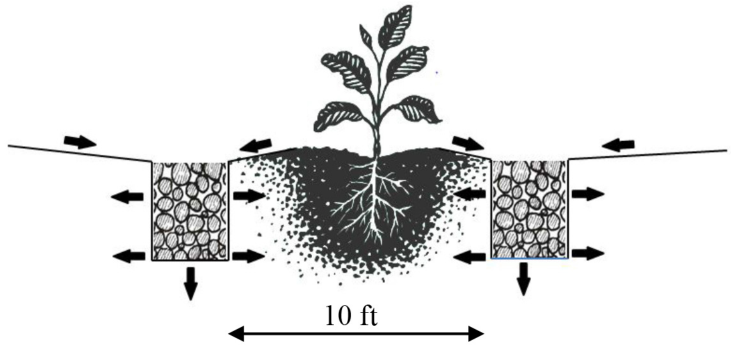
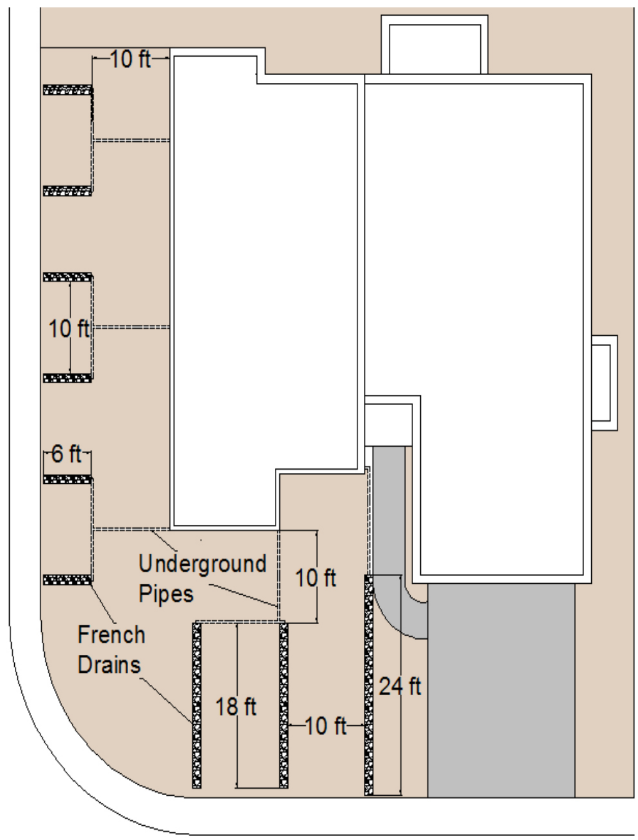


FIGURE 12. Offset infiltration trenches.



The designed infiltration trenches were placed 10 feet apart and trees and/or shrubs were planted in between (Figure 12). The advantage of the small surface area of infiltration trenches is the reduction of loss of water through evaporation and wide distribution of the stormwater over the lawn area that gives more flexibility for the owner to place the plants.

FIGURE 13. Set of infiltration trenches for model home, many other options with equal storage volume are possible.



RESULTS

Since the surface conditions of the micro-watershed were kept the same for the four example cities, the resulting volumes of the 1 × 1 square foot infiltration trenches were all equivalent to 96.25 cubic feet (13% of the soil area). This volume was distributed over the soil area as shown in Figure 13. Stormwater from the roof was transmitted 10 feet away from the building to the infiltration trenches by buried pipes.

While the infiltration trench size was the same for all cities, the size of passively sustained landscape (taken as the sum of the crown area of all the plants) resulting from each simulation varies between cities depending on the climatological and soil conditions.Tables 4, 5 and 6 show the results for the three different scenarios of setting the landscape plants (only trees, trees and shrubs, and only shrubs). Other results including groundwater recharge, offsite runoff, and water savings for each city were obtained from the water balance simulation and are shown in Table 6.

The size of the infiltration trenches was equivalent in the four study cities due to the similarity of the micro-watershed condition and the selected design storm. The trench volume controls the amount of stormwater that will run off the watershed, as can be seen in Table 6,

TABLE 4. Passively Sustained Green Area Percentage in the Micro-watershed.

City	Landscape vegetation /micro-watershed area (%)		
	Only Trees	Trees and Shrubs	Only Shrubs
El Paso	22	25	27
Albuquerque	28	33	38
Phoenix	19	25	26
Pahrump	14	16	18

TABLE 5. Passively Sustained Green Area Percentage in the Soil Area.

City	Landscape vegetation/soil area (%)		
	Only Trees	Trees and Shrubs	Only Shrubs
El Paso	36	41	44
Albuquerque	45	54	62
Phoenix	31	41	42
Pahrump	22	26	29

TABLE 6. Water Budget Results.

Planting Scenario	City	Groundwater Recharge (in/yr.A_w)*	Offsite Runoff (in/yr.A_w)	Water Savings (in/yr.A_w)
Only trees	EL Paso	0.74	0.51	0.52
	Albuquerque	0.00	0.16	0.57
	Phoenix	0.38	0.37	0.48
	Pahrump	0.00	0.33	0.31
Trees and Shrubs	EL Paso	0.95	0.51	0.49
	Albuquerque	0.00	0.16	0.56
	Phoenix	0.09	0.37	0.53
	Pahrump	0.01	0.33	0.31
Only Shrubs	EL Paso	1.44	0.51	0.43
	Albuquerque	0.39	0.16	0.51
	Phoenix	0.60	0.37	0.44
	Pahrump	0.18	0.33	0.28

*Inches/year per micro-watershed Area.

where the offsite runoff value for the same location was not affected by landscape planting scenario. On the other hand, the runoff amount varies between cities due to the different precipitation patterns. Among the cities, Albuquerque has the largest passively sustained landscape vegetation area, even though it receives the same amount of precipitation as El Paso. This result from the more favourable distribution of the precipitation along with the low evapotranspiration rate in Albuquerque as a result of its higher geographic elevation.

In the scenario where only shrubs were planted, a larger landscape vegetation area was obtained because of the low water requirements particular to shrubs. In this scenario, more stormwater infiltrated as groundwater recharge, because less was lost to evapotranspiration.

However, in some cases such as Pahrump and Albuquerque, when the planting scenario was "trees" or the combination of "trees and shrubs", there was no surplus water for recharge because all the water was used to satisfy the landscape vegetation requirement. An alternative to the no supplemental watering scenario shown in Tables 5 and 6 would be to allow homeowners to add supplemental water to their landscape only during the dry season. If one inch of supplemental watering were to be allowed only in the annual dry season, the amount of landscape supported by passive rainwater harvesting increases by 14% in El Paso, 4% in Albuquerque, 18% in Phoenix, and 20% in Pahrump.

CONCLUSION

An example home, representative of modern subdivisions, was used to illustrate how passive rainwater harvesting can be used to support landscape growth in desert climates. The impermeable surfaces, specifically the large ratio of impervious surface to remaining soil area characteristic of modern subdivisions (big houses on small lots), means that excess water relative to climatic norms, is available for landscape watering. This water is captured during rainstorms in small infiltration trenches in the lot and then infiltrated into the surrounding soil for storage. Landscape cloth and mulch are used to prevent weed growth that would result in non-productive water loss from the soil.

The methodology explained herein is flexible. For example, the system might be designed such that the vegetation never needs to be watered, as was the case with the main simulations in this paper. Alternatively, landscapes might be designed such that the vegetation must be watered only in the annual dry season or only in extreme drought periods (i.e., about once per decade). The passive rainwater landscape design could also be primarily used to increase the groundwater recharge when minimal or no vegetation is planted around the infiltration trenches.

The net result of the method proposed here is that fairly lush vegetation density can be supported within residential areas without additional use of municipal potable water. The same modifications also reduce stormwater runoff and increase groundwater recharge. Since water tanks and sprinklers are not required, the suggested changes do not increase landscaping costs, and only require that a knowledgeable design with precise matching of water supply and demand substitutes traditional irrigation and sprinkling practices.

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