Rainwater as a Potential Resource for Water Independence in Tucson's Communities

Making Action Possible in Southern Arizona (MAP Dashboard)

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Executive Summary

The United States Southwest is experiencing what some believe to be the worst drought in 500 years (Kuhn, 2016). Studies have projected that the region will experience a more arid climate and higher risk of water shortages over the coming century (Ault, 2016). Similar to many cities in the region, the City of Tucson is dependent on water supplied from the Colorado River in addition to its own deep aquifer, a non-renewable source.[1] This imported supply equates to over 20 percent of the 90 billion gallon annual demand serviced by Tucson Water with approximately 20 billion gallons of Colorado River water transferred a year (Tucson Water Department, 2015).[2] Although the Tucson municipality does not expect to have to cut supplies from the Colorado until 2030 (Tucson Water Department, 2015), Colorado River supply shortages may be declared as early as next year (USBR, 2015). While water resources become scarce, population in the region has grown considerably in the past decades and the growth is expected to continue. In Arizona, the population is anticipated to increase by 25 percent between the years 2012 and 2030, with a 17 percent increase in the Tucson Metro area (ADWR, 2014). The imbalance between available water resources and projected water demands in the coming years presents tremendous challenges for water resource management, necessitating the development of novel strategies and tools to meet the growing demand. Along with many cities in the Southwest, Tucson is faced with a challenge: How can a cost effective, equitable and sustainable water supply be devised for a growing population? What strategies can be used to realize water independence in the region?

To become water independent, Tucson will need to eliminate or offset this imported water dependence through a combination of conservation, water reuse, and expanded alternative sources. Enhancing the use of alternative sources that are local and renewable is one way to balance the water budget and to increase Tucson's resilience to changes on the Colorado River. [3] Rainwater has drawn increasing attention as a possible solution to the local deficit as, in sheer volume, annual precipitation would more than account for all of Tucson's annual need. As an example, in 2016, Tucson Water supplied over 87 thousand acre-feet (28.4 billion gallons) within the city boundary and adjacent service areas. In 2016, over 125 thousand acre-feet (40.7 billion gallons) of rain fell within the city boundary, matching the total annual Tucson Water demand by 144 percent. Only less than two percent of the rain that falls in Tucson recharges naturally. To utilize rainwater, it must be locally managed. However, rainwater is a distributed resource that must largely be gathered in decentralized interventions, rather than one large public works construction. Since amounts of precipitation fluctuate in daily volumes and seasonal patterns, active storage must be considered. To leverage this resource, a new model of public works improvement must be developed.

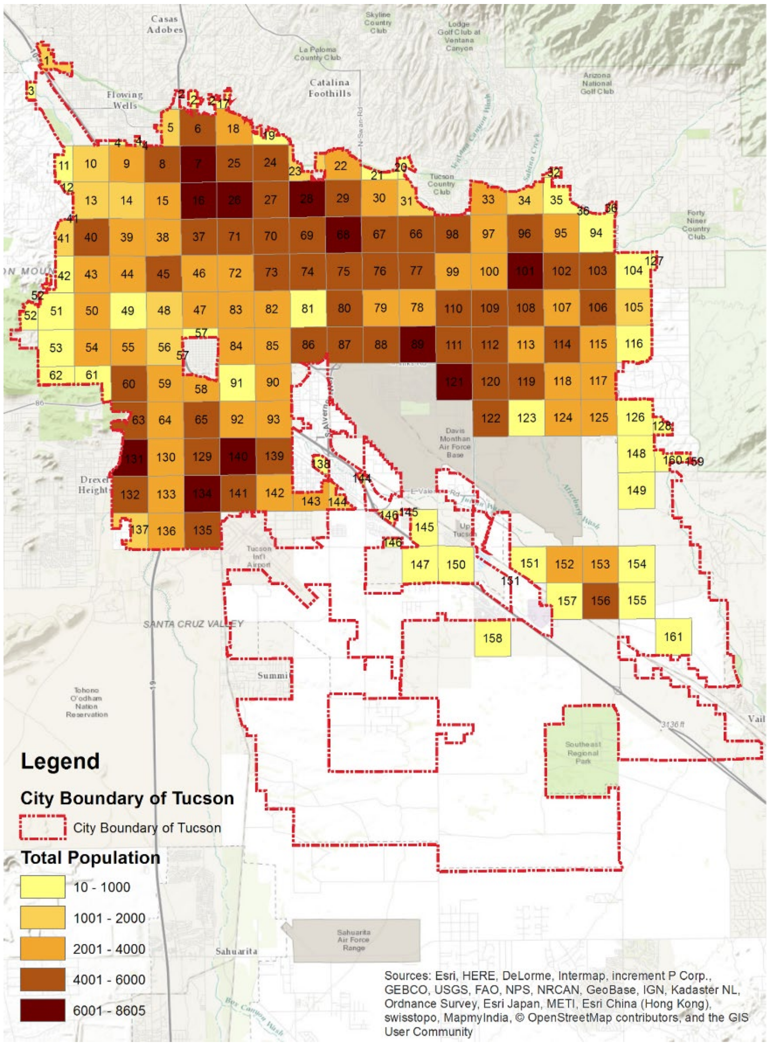


Figure 1 Total population of each of 161 township sections

This white paper assesses the City of Tucson's capacity to achieve water independence using rainwater. To complete this analysis of decentralized system capacity for the total Tucson metropolitan area, the project divides the city into 161 one-mile by one-mile township sections (*see Figure 1)*, each functioning as an independent system. Remote sensing technology is used to isolate the variables of roof areas, material run-off coefficients, monthly irrigation demands of existing vegetation, and impervious land cover. To determine the irrigation demands, the project team created a vegetation classification system of sixteen categories, each isolated through a multi-step LiDAR and normalized difference vegetation index (NDVI) process. Ultimately, a dynamic system model was built to evaluate the storage volume needed to reach and maintain water independent system resilience over a 10-year period in each township section. The 10-year period model is representative of the future mega-droughts that have been projected to occur in the region by recent climate models (Ault, 2016). The project consists of four analysis modules: daily rainwater harvesting potential estimation for passive and active systems (i.e., supply), daily water needs computation for indoor and outdoor (i.e., demand), water independence assessment (i.e., systems analysis balancing daily supply and demand), and scenario and policy analysis through identification of disadvantaged areas/neighborhoods for subsidy consideration.

The paper discusses two water independent system cases: (1) to replace all Tucson's water demand with harvest rainwater and (2) to replace Tucson's current imported water demand from the Central Arizona Project (CAP) with rainwater. The model provides evidence that Tucson can technically achieve a resilient water independent system through its rainwater supplies, measured over a 10-year period. Figure 2 shows the geography of supply relative to demand by township section. In order to completely replace the imported water supply, the model found that passive harvesting systems would meet the great majority of current estimated outdoor irrigation demands and active rainwater harvesting systems could supply indoor water demands and the remaining outdoor water needs.

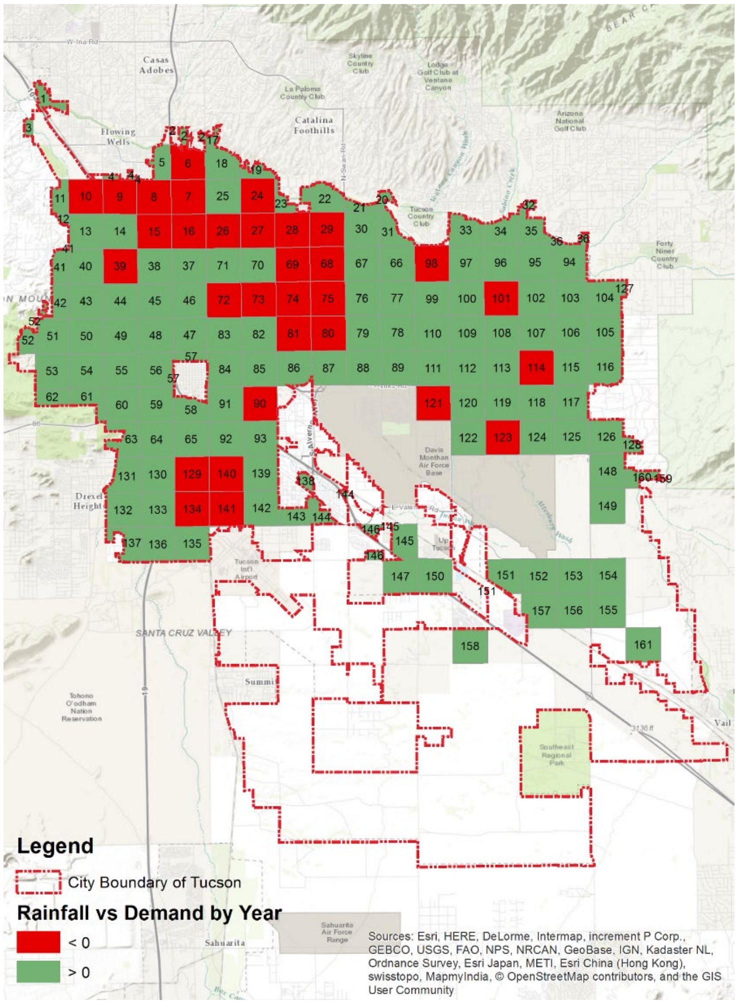


Figure 2 Annual Rainwater Supply vs Water Demand (2007-16)

The most feasible case for implementation in the paper is Case B of System 2 (*see figure 3)*. In this case, the storage volumes necessary to reach local water budget balance is on average 10,000 gallons per 1,000 square-feet of roof area but vary over the 161 township sections due to differences of per capita water use in various parts of the city. A storage capacity of 1,000 gallons required per 1,000 square-feet of roof area is the lower bound and 200,000 gallons of storage capacity required per 1,000 square-feet of roof is the upper bound. To make decentralized infrastructure intervention practical at the upper bound, significant conservation and cooperative water resource sharing between township sections would be required to lower the required storage capacity. For relative visual, the average size of a backyard swimming pool is 10,000 gallons. A typical, domestic 10,000-gallon active rainwater harvesting system with a treatment system capable of potable water standards costs $10,000 to install (inclusive of hard and soft costs) (Texas Water, 2017). The financial cost implications of the resultant, required active storage volumes render many of the modelled scenarios impractical, especially for lower income residents without additional incentives. For this assessment, decentralized systems were assumed to require private residential investments. The private residential investment was defined as the cost of constructing the active storage volumes produced by the model.

The most promising policy implication provided by this model is in areas of low required investment in storage and high potential societal returns from the co-benefits of rainwater harvesting. Rainwater harvesting has been proven to provide co-benefits such as increase aquifer recharge (Dillon, 2005), positively modify microclimates by increasing moisture content and evapotranspiration (Hamel et al., 2012), mitigate heat island (Furumai, 2008; Coutts et al, 2012), and decrease water system energy use (Jiang et al., 2013). Optimal areas for rainwater harvesting were defined as the township sections with the smallest active storage volume resultants in the model. Due to these smaller active storage requirements, these township sections require the lowest investment to achieve water independence in the model. When these results are overlaid with the current adoption locations of Tucson Water's Rainwater Harvesting Rebate Program, there is a clear discrepancy between rebate locations and optimal locations. Areas of Tucson with high poverty correspond with optimal harvesting township sections. The study finds significant socioeconomic disparity in the rainwater rebate program adoption and supports recent policy that modified the rebate program to better target its impact and increase its impact on environmental, economic, and social betterment.

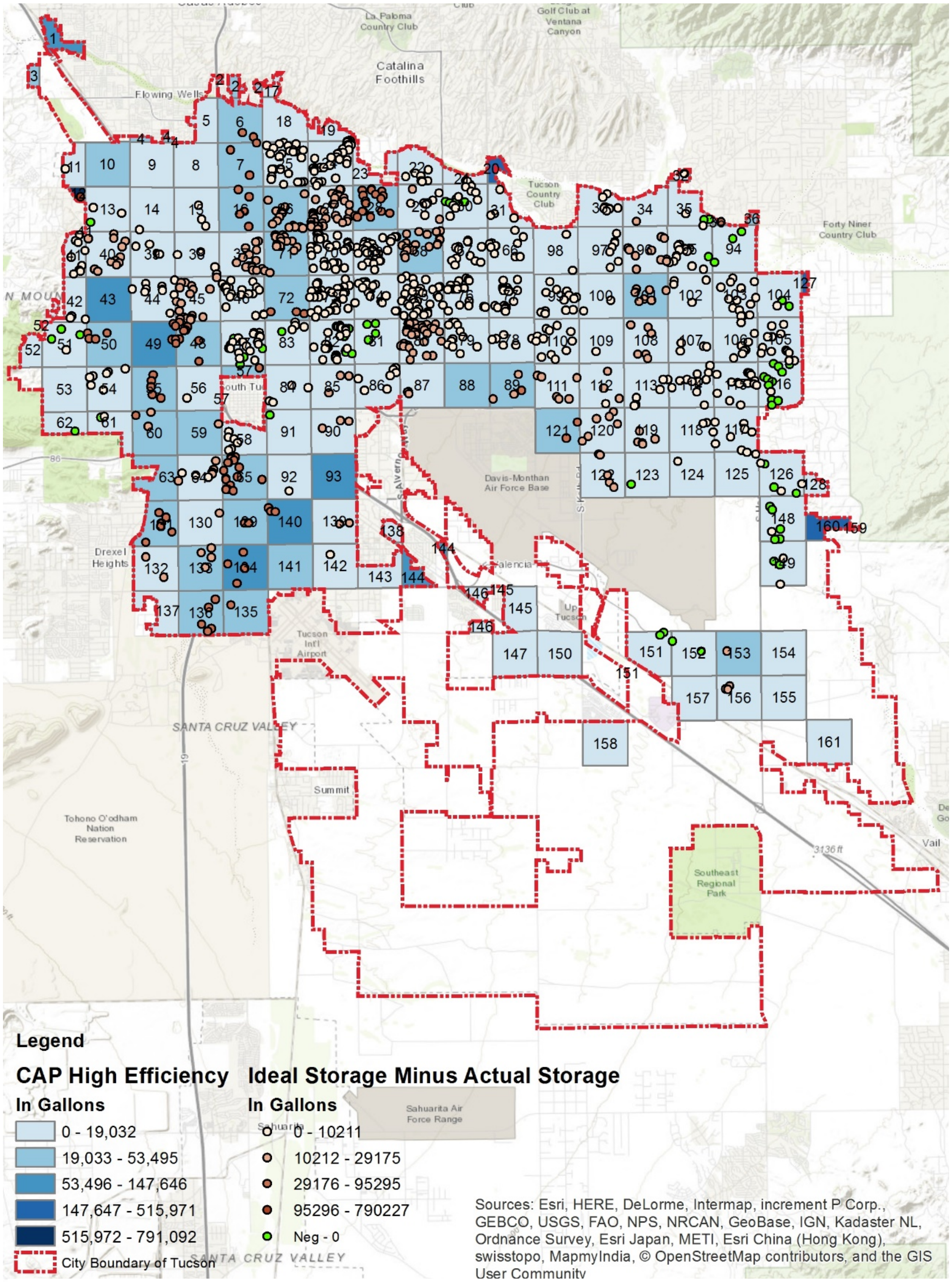


Figure 3 Case 2B: required storage per 1,000 sf roof area for each township to achieve water independence

1. Introduction

The United States Southwest is experiencing what some believe to be the worst drought in 500 years (Kuhn, 2016). Studies have projected that the region will experience a more arid climate and higher risk of water shortages over the coming century (Seager et al., 2007). While water resources become scarce, population in the region has grown considerably in the past decades and the growth is expected to continue. In Arizona, the population is anticipated to increase by 25 percent between the years 2012 and 2030, with a 30 percent growth in Phoenix Metro and a 17 percent increase in Tucson Metro (ADWR 2014). The Arizona Department of Water Resources (ADWR) determined that in 25 years Arizona will need to come up with an additional 900 thousand acre-feet of water to meet projected shortages. In 100 years, Arizona's water demand will outweigh supply by about 3.2 million acre-feet (ADWR, 2014). Having a reliable source of water is key for enabling sustainability and economic growth (Jacobs, 2016).

Currently, the City of Tucson is dependent on water supplied from the Colorado River in addition to its own aquifer and reuse programs. According to the US Bureau of Reclamation, Colorado River supply shortages may be declared as early as 2018 (USBR, 2015). The imbalance between available water resources and projected water demands in the coming years presents significant concern for water resource management, necessitating the development of novel strategies and tools to meet the growing demand. Along with many cities in the region, Tucson is faced with a challenge: how to devise a cost effective, equitable and sustainable water supply for a growing population? What strategies can be used to realize water independence in the region?

Water independence or net zero water, on the municipal scale, is defined as an ability to supply a population's water needs within local resources. Currently, Tucson imports approximately 20 billion gallons of Colorado River water a year, over 20 percent of the 90 billion-gallon annual demand (Tucson Water Department, 2015). To become water independent, Tucson will need to eliminate or offset this imported water dependence through a combination of conservation, reuse, and expanded alternative sources. Rainwater has drawn increasing attention as a possible solution to the local deficit as, in sheer volume, annual precipitation would more than account for all of Tucson's annual need. As an example, in FY 2016 Tucson Water supplied over 87 thousand acre-feet (28.4 billion gallons) within the city boundary and adjacent service areas in the foothills and South Tucson. In 2016, over 125 thousand acre-feet (40.7 billion gallons) of rainwater fell within the city boundary. However, rainwater is a resource that must be gathered in decentralized interventions, rather than one large public works construction. To leverage this resource, a new model of public works improvement must be developed.

Although numerous studies exist on the individual system dynamics of rainwater harvesting, little research has evaluated the potential of these decentralized systems to impact urban water challenges as a network. In a recent review of National Science Foundation (NSF) sponsored studies and workshops on the energy-water-food nexus, Armstrong et al. (2018) identify a pressing research gap in simulation of solutions to water stress at a community scale that isolate variables for accurate analyses. In a recent comprehensive review of rainwater harvesting research, Campisano et al. (2017) point to a need for further study on the best methods to model RWH at larger scales. This article bridges these gap and addresses these research needs by proposing a method of simulating a network of decentralized passive and active systems across Tucson, Arizona. The research evaluates the necessary infrastructural investment to reach the goal of urban water independence.

The study site, the City of Tucson, Arizona has a population of approximately 527,586 (American Community Survey, 2016). The City of Tucson lies within the Tucson Metropolitan Statistical Area (MSA). In 2013, the poverty rate of the Tucson MSA was 20.2 percent, which was the second poorest among the twelve Western U.S. MSAs (MAP, 2016). The study area is well-suited for the proposed research for the socioeconomic diversity of its residents and uneven spatial distribution of flooding. Wide gaps are found in income and educational attainment.

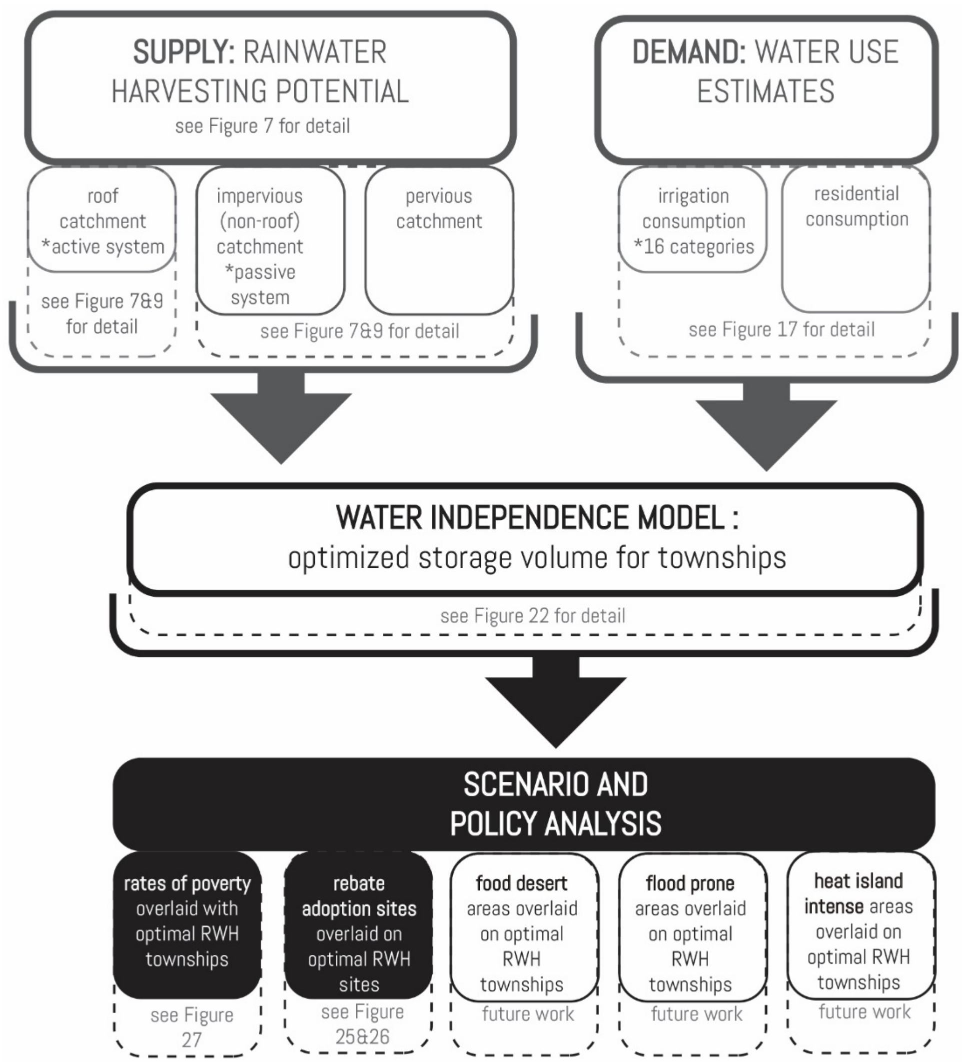


Figure 4 Flow chart of the overall modeling and analysis process undertaken.

Tucson Water has pursued expanded rainwater harvesting as one of several strategies to address the current local supply-demand gap through a rebate incentive program available throughout its service jurisdiction. Rainwater is harvested through passive or active systems. Passive systems are designed to retain water until it can be naturally absorbed into the land (curb cuts with swales and pervious pavers are common passive strategies). Active systems, by comparison, collect, (sometimes) clean, and store rainwater for reuse (storage is the defining component of active harvesting). In this paper's model, we assume water harvested passively is used to offset irrigation demands, whereas the water harvested through active systems can be stored and employed to meet non-potable and potable demands, depending on the treatment level achieved. To address Tucson's future supply-demand deficit, a combination of passive and active rainwater harvesting systems will be needed. Using the past 10 years of precipitation data, this white paper evaluates the potential of Tucson to reach water independence through rainwater by modeling two related systems: passive harvesting (rainwater harvested from streets and pervious surfaces) and active harvesting (rainwater harvested from roofs). Also, the research locates the areas of implementation of highest priority by overlaying socioeconomic data and current rainwater harvesting rebate adoption sites. The aim of this work is to aid in understanding how Tucson will address the upcoming water supply-demand gap and evaluate modifications to the rebate program to increase its potential impact on environmental, economic, and social betterment.

2. Methods

Our study was conducted in the City of Tucson (see *Figure 5 and 6*). The area consists of 161 township sections (1x1 square miles), accounting for 49.55 percent of the entire Pima county population. Based on the 2015 American Community Survey (ACS), *Figure 5* shows the spatial distribution of population and *Figure 6* maps the percentage of people under poverty. As *Figure 6* shows, high poverty areas are concentrated in the central area as well as South Tucson.

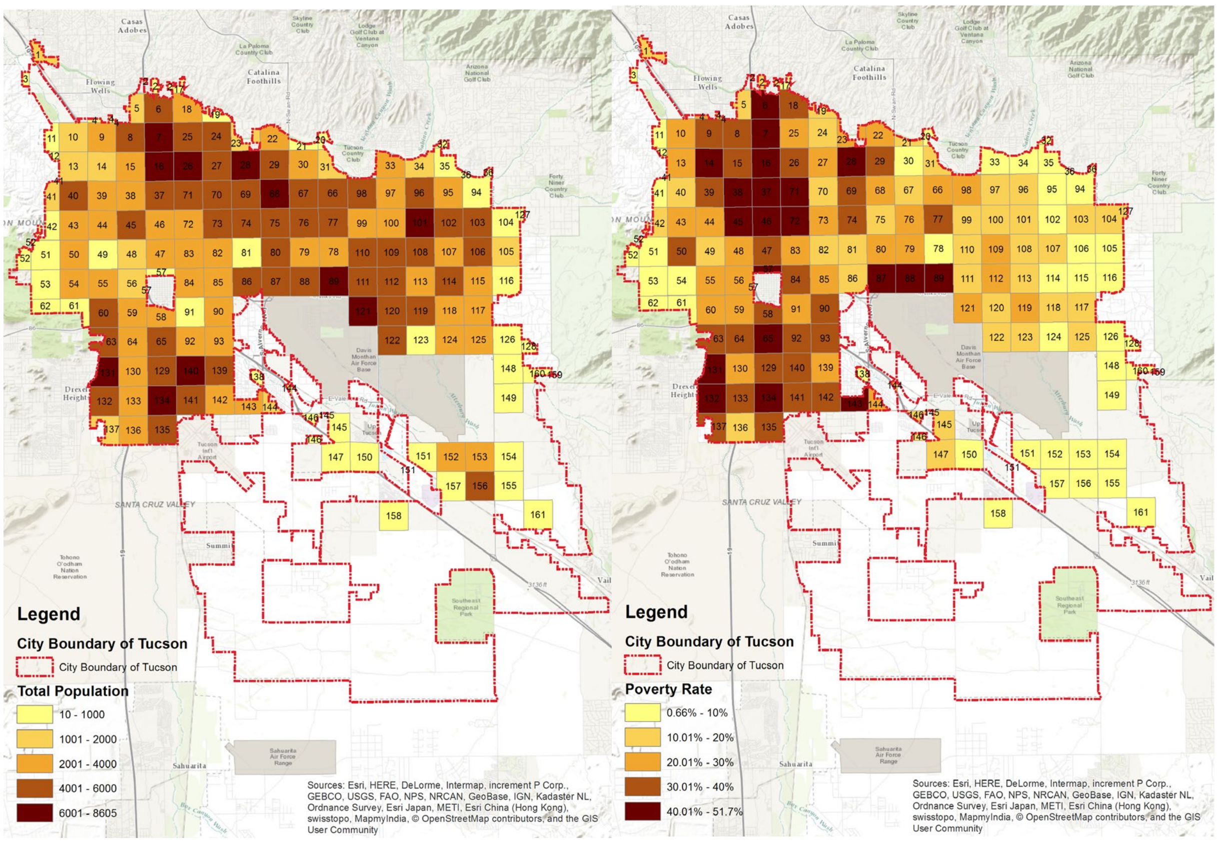


Figure 5 (left) Total population of each township section

Figure 6 (right) Poverty rate of each township section

The data collected for this study included remote sensing data, LiDAR data, weather data, and demographic and socioeconomic data. *Table 1* summarizes the data and the associated data sources.

Table 1 Data source summarization

Data	Description	Data Source
LiDAR LAS (Log ASCII Standard) files	Point clouds with x (longitude), y (latitude), and z (elevation) coordinates for 161 Tucson residential township sections	Pima Association of Governments (PAG) LiDAR data accessed from the University of Arizona Libraries
Parcel data	Parcel polygons shapefile, metadata, and parcel use code descriptions	Pima County GIS ftp server
Socioeconomic data	Number of residents and workers by sex, number of households, poverty	U.S. Census Bureau, 2011-2015 ACS 5-Year Estimates
Remote sensing data	High Resolution Orthoimagery (HRO) from PAG with a spatial resolution of 6 inches. The orthophoto was taken in 2015 between May and June, with 4 bands covering RGB and NIR. The radiometric resolution is 8-bit unsigned.	PAG orthophoto accessed from University of Arizona Library
Global Historical Climate Network Daily (GHCN-Daily) Precipitation data	Daily rainfall gauge observation from 2007 to 2016 with the unit of inch in the format of csv. A total of 200 stations' daily precipitation was included.	National Oceanic and Atmospheric Administration (NOAA)
Normalized Difference Vegetation Index (NDVI) data	An indicator used to identify vegetated areas and their conditions	PAG
Tucson Rainwater Harvesting Rebate adoption sites	Point locations within the City that have used Tucson Water's Rainwater Harvesting Rebate program to install active systems in the last four years	Tucson Water
Tucson food desert current areas	Areas of the City that experience food desert conditions or geographically isolated location where access to healthy, affordable food is absent or limited.	Bao and Tong 2017

3. Rainwater Harvesting Potential Estimation

The first stage of the project was to create an integrated model of rainwater capture in Tucson. Rooftops served as the main active water harvesting means as they have been considered as the first and most effective choice for the catchment of rainwater (Haq, 2017). The rainwater harvesting potential (in gallons/year) of a roof was estimated based on the local precipitations (P, in feet/day), the catchment area (A, in square-feet) and the runoff coefficient (RC, nondimensional) (Farreny et al., 2011). In this study, rainwater harvesting potential is estimated with the precision of daily feedback between local precipitations (P, in feet/day over 10 years), the catchment area within 161 township sections (A, in square-feet) and the runoff coefficient (RC, nondimensional). An illustration of the rainwater harvesting potential estimation was provided in *Figure 7*.

3.1 Precipitation Estimation

Although PRISM and the National Weather Service provide spatially continuous daily climate data that were interpolated based on weather stations, the resolution of this free data source is 4 kilometers with one grid, covering about four township sections. It is too low for our study as the simulation of rainwater system needed to be performed at the level of township section. Based on the precipitation data collected by 200 stations in the study area (GHCN-Daily), ordinary kriging models were constructed to generate precipitation estimates for sites where no observations were available. Kriging is one of methods that have been widely used to make spatial interpolations. The most critical component of kriging lies in the semi-variogram, a model used to describe how a spatial phenomenon varies across space and with distance. The empirical variogram was calculated using the following equation, where *i,j* indicates station sites and z_i and z_j are the associated precipitation observations; *d* is distance; *n(d)* is the number of pairs of observations that are *d* away from each other.

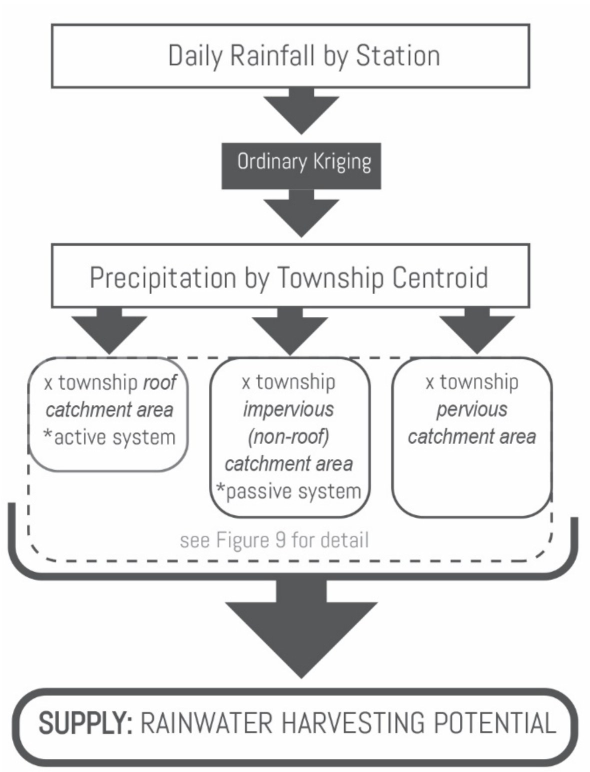


Figure 7 Rainwater Harvesting Potential with Precipitation

$$2\hat{\gamma}(d) = \frac{1}{n(d)} \sum_{d_{ij=d}} \left(z_i - z_j\right)^2$$

An illustration is given in *Figure 8* to show the semi-variogram and fitted model based on the precipitation on Sept. 1, 2016.

Kriging was run for each day of 10 years (3653 days) from year 2007 to year 2016 with estimates generated. The rainfall for a township section was approximated using the precipitation estimate at the township section centroid. The exponential model was chosen to construct the semi-variogram as it gave the best model fit based on cross validation tests. The rainfall amount at each station ranged from 0.00 feet to 0.42 feet.

3.2 Catchment Areas

Three main catchment types were used in the model simulation:

1. Impervious (non-roof) catchment = passive rainwater harvesting area
2. Pervious catchment = natural irrigation area
3. Roof catchment = active rainwater harvesting area (further divided into runoff coefficient types: tile, shingle, and flat)

Passive rainwater harvesting was simulated using impervious non-roof catchment. Active rainwater harvesting was simulated using roofs as the exclusive catchment for the system.

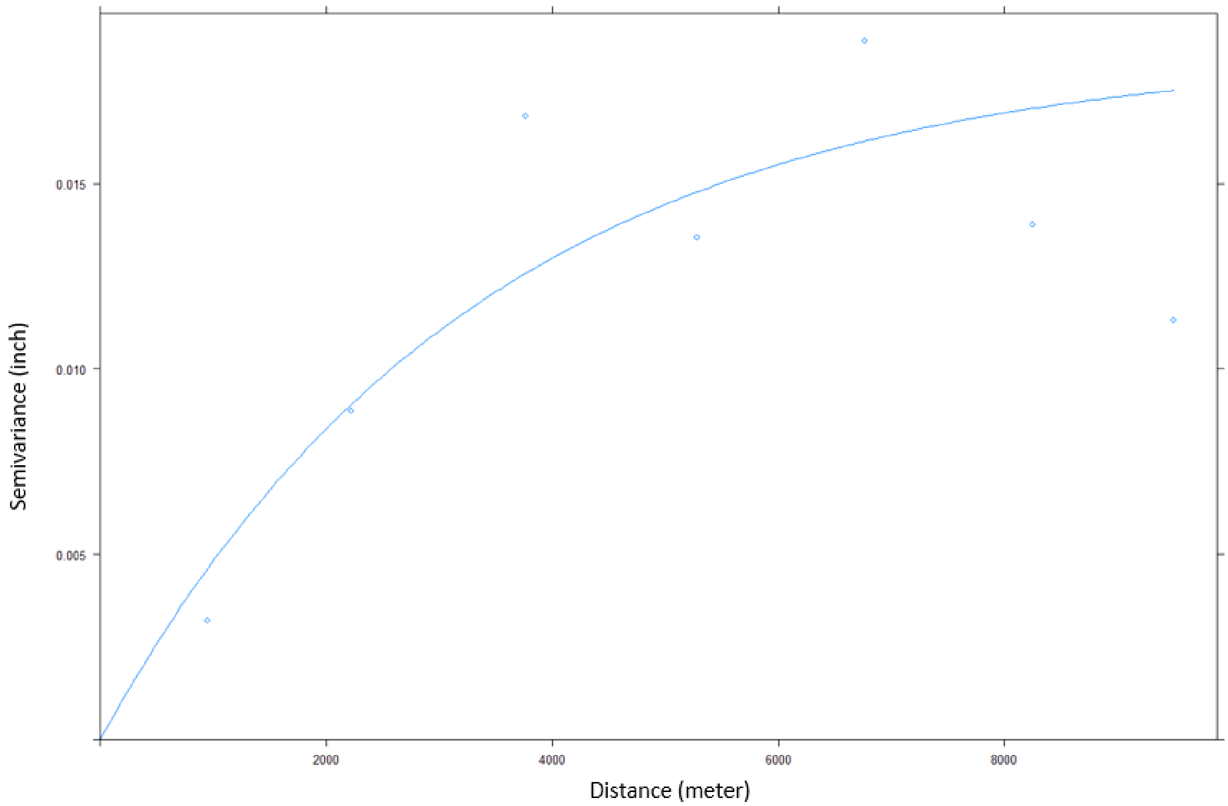


Figure 8 Semivariogram and fitted model on the date 09/01/2016

3.2.1 Roof Catchment: Rooftop print from LiDAR data

The roof catchment area was estimated based on LiDAR point clouds provided by PAG. The full process is illustrated in *Figure 9.* We used an ArcGIS extension, *LiDAR Analyst*, to process LiDAR LAS files. Two primary datasets were derived from the raw LiDAR data (i.e., first-return and last-return data). While the first return data contain the elevation information of the tallest features, the last return data often record the actual ground surface. The two data sets were used to derive digital surface model (DSM) and the bare earth layer, digital terrain model (DTM). These data were then used to extract building roof prints. The outputs of the extraction are polygon features with a roof type attribute classifying roofs into flat roofs and sloped roofs. The spatial resolution of computation was 1 foot. *Figures 10 to 14* give an illustration of LiDAR raw data, the first-return and last-return data, the bare earth layer and the extraction results of building roofs.

3.2.1.1.1 Runoff coefficients

The runoff coefficient (RC) assesses the portion of rainfall that becomes runoff, taking into account losses due to spillage, leakage, catchment surface wetting and evaporation (Singh, 1992). The RC is useful for predicting the potential water running off a building roof, which can be conveyed to a rainwater storage system.

RC values vary greatly depending mostly on the slope and the roughness of the roof. In this study, roof types were grouped in the following two broad categories: flat roofs and sloped roofs. The sloped roofs were further divided into two categories based on the roof material: shingle and tile. The RCs of these three types of roofs were estimated based on the existing literature (see *Table 2*).

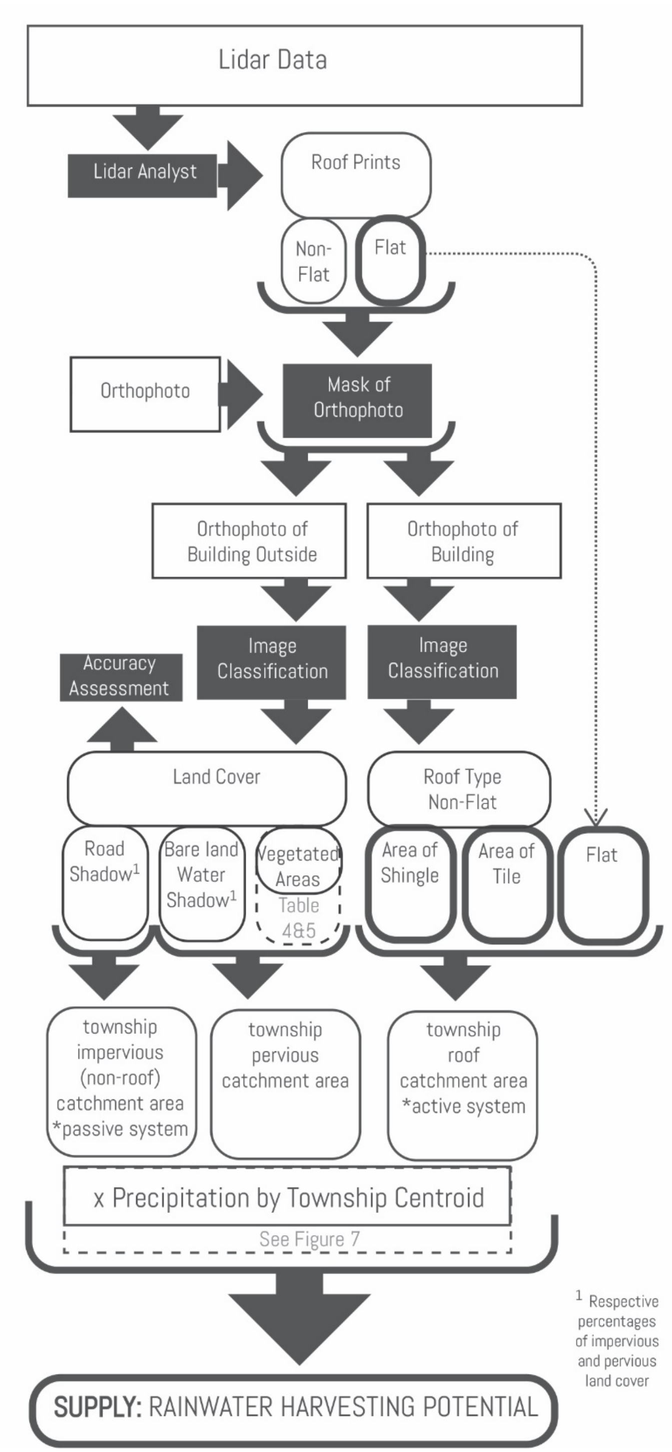
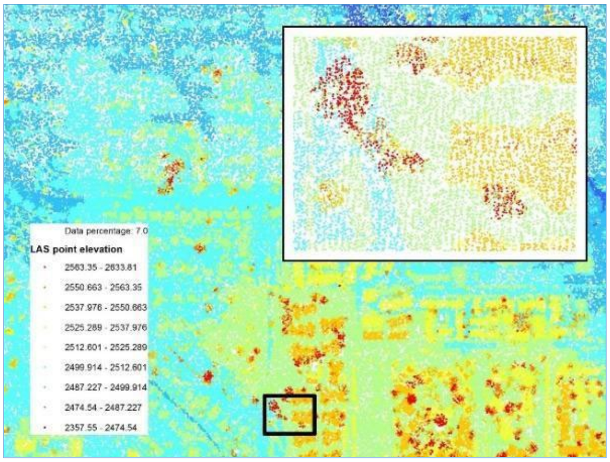
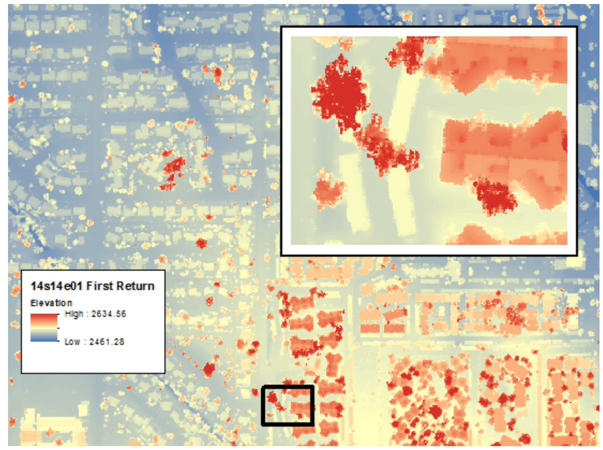
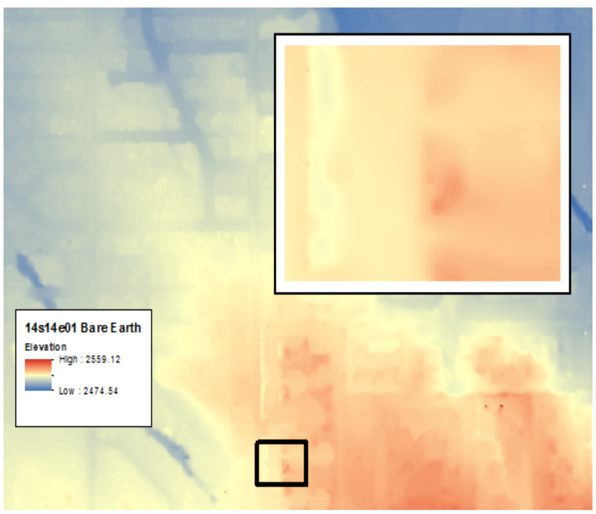


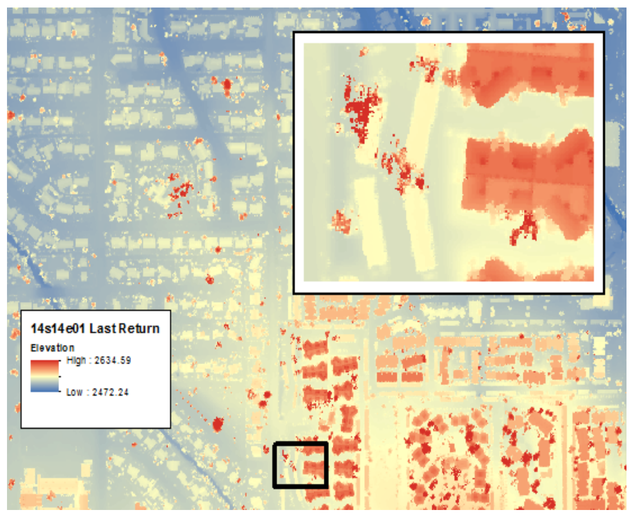
Figure 9 Rainwater Harvesting Potential with Catchment Surfaces Classified

After the roofs were identified in Section 3.2.1, the roof type attribute resulted from *LiDAR Analyst* tool were used to identify flat roofs and sloped roofs. The tile and shingle sloped roofs were further identified using Maximum Likelihood Image Classification. To increase the accuracy, roof data were also segmented using the spectral separation of three bands: visible red Band 1, visible blue Band 3 and near infrared Band 4. The spectral reflectance among the three bands trained for the four groups of shingle, tile, vegetation, and shadow, as some roofs were covered by trees or shadow (also see *Figure 15* and *Figure 16*). As the roof type data did not match perfectly with the orthophoto, vegetation and shadow types were also included in the classification. The spectral reflectance signature was trained with 110 samples covering 150,000 pixels collected from the study area, mainly for the shingle and tile materials. An accuracy assessment based on 295 points was performed. The overall accuracy is 85.42 percent.









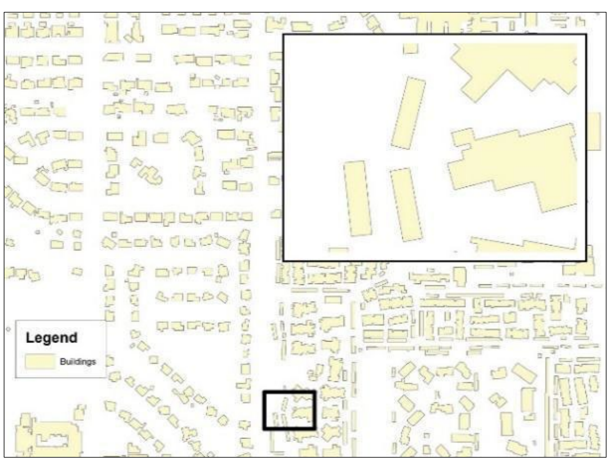


Figure 10 Point clouds of LiDAR dataset for part of area township: 14S, range: 14E, section: 01

Figure 11 The result of first return for part of area township: 14S, range: 14E, section: 01

Figure 12 The result of last return for part of area township: 14S, range: 14E, section: 01

Figure 13 The bare earth for part of area township: 14S, range: 14E, section: 01

Figure 14 Building roof prints for part of area township: 14S, range: 14E, section: 01

Table 2 Runoff coefficients used in the study

Roof types		Runoff coefficients in literature	Runoff coefficient estimation
Flat roofs		0.6 – 0.7 (Haq, 2017) 0.7 – 0.81 (Farreny et al., 2011)	0.7
Sloped roofs	Shingle	0.9 (Farreny et al., 2011)	0.9
	Tile	0.8 – 0.9 (Jayasuriya et al., 2014)	0.85

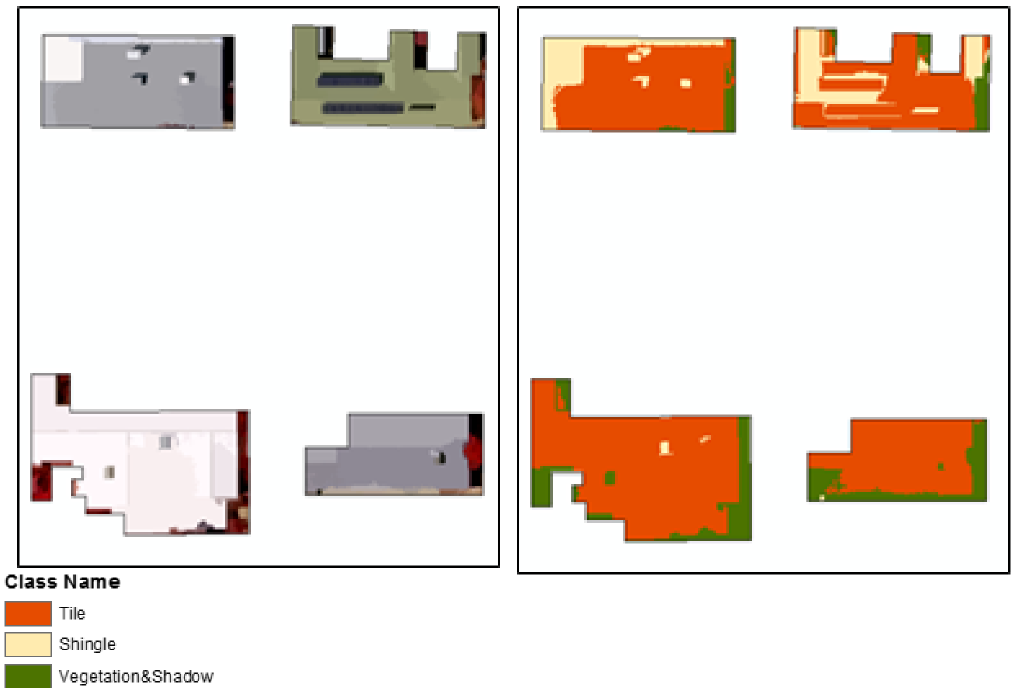


Figure 15 (left) Original roof material image

Figure 16 (right) Roof image classification results

3.2.2 Impervious (Non-Roof) Catchment: Stormwater

Runoff of stormwater is calculated with area of impervious land cover and using a runoff coefficient. The impervious land cover includes roads, parking lots, sidewalks, and other solid ground conditions. Roof area is excluded as it is part of the active rainwater harvesting system. A hybrid image classification method was performed using a 2015 aerial orthophoto photography with 6-inch resolution to identify pervious and impervious surfaces. To increase the accuracy of the image classification, roof area was extracted and excluded first. Then, the visible red band 1, visible blue band 3, and near infrared band 4 of the orthophoto were combined and segmented into groups with similar spectral values. Finally, a supervised classification was conducted to differentiate pervious from impervious land cover. Eight classes of land cover types were included in the supervised image classification - road, driveway, vegetation, bare land, water pool, lake, shadow, and rubber tennis courts (or sport courts). Due to the limit on radiometric resolution of the orthophoto, rubber land cover and vegetation tended to mix up, and lakes were difficult to distinguish from shadow. To remedy the issue, image classification results were post-processed through manual detection and correction based on a comparison using Google Maps. These land covers were then reclassified into just three types - pervious, impervious, and shadow. The accuracy assessment based on 200 points on pervious vs. impervious land cover was 93 percent.

3.2.3 Pervious Catchment

Natural irrigation occurs through rainfall on pervious surfaces. The pervious land cover includes vegetation, bare land, and water body (pools and lakes). Pervious surfaces were identified using the above method, in parallel with impervious surface classification. Pervious land cover was further classified into five main subcategories, each with a species factor. Section 4.0 describes this classification and *Figure 17* details the process.

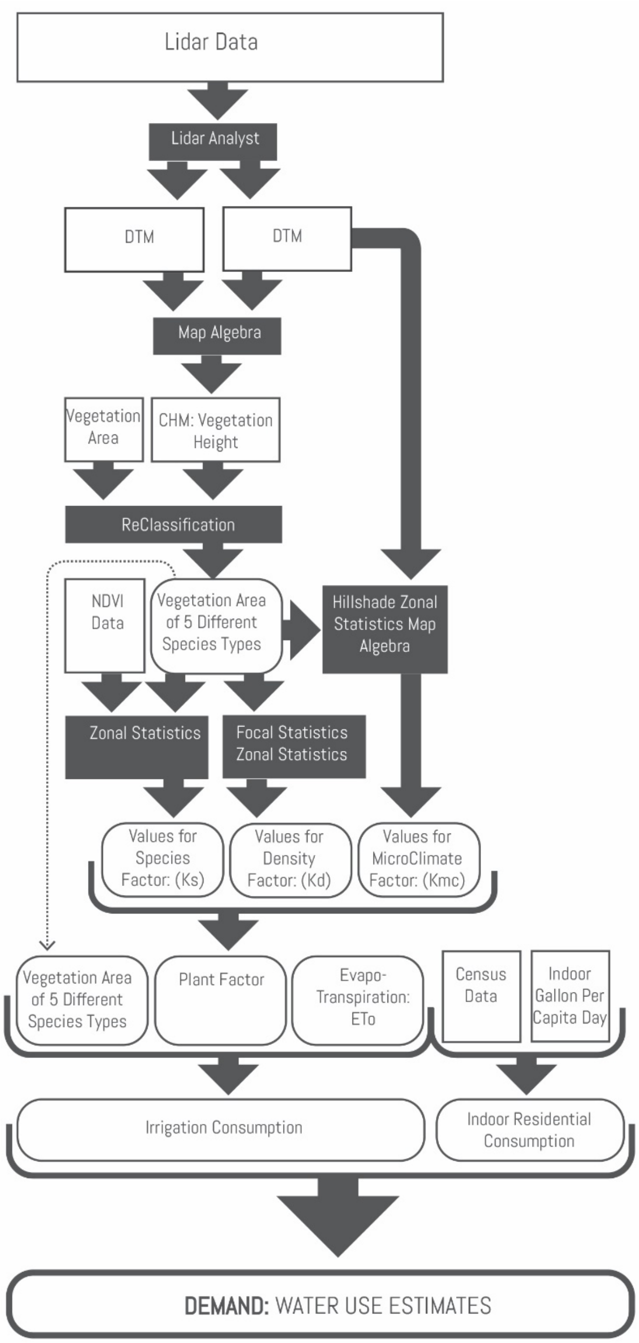


Figure 17 Water Demand with Irrigation and Residential Consumption

4. Water Needs Estimation

In this study, water consumption was estimated for outdoor irrigation and indoor residential use. Indoor use was estimated using the most recent value for gallons per capita day (GPCD) for the City of Tucson and multiplying by the census population data of residents within each township section. Outdoor irrigation demand was estimated using a combination of remote sensing methods and meteorological data for the City of Tucson. Species factor (ks), microclimate factor (kmc), and density factor (kd) were estimated with remote sensing technique described below. Evapotranspiration (ETo) was taken from publicly supplied data on monthly ETo for the study years (2007-2016) from the Arizona Meteorological Network (AzMet) at the University of Arizona.

4.1 Irrigation Consumption: Outdoor Vegetation

The areas of vegetation are derived by supervised classification. See *Table 5* for a summary of the coefficients, resulting in sixteen vegetation types. Different types of vegetation have different water needs for irrigation, which influences overall irrigation demand. We first categorized vegetation based on height. A canopy height model (CHM), which contains information of the vegetation height, is created by using the digital terrain model (DTM) and digital surface model (DSM) derived from LiDAR data.

Considering the shape of tree canopy, to avoid the center and the periphery of one tree to be classified into different vegetation types. Vegetation was first classified into two classes based on height using CHM: groundcovers (vegetation height < 3-feet) and trees (vegetation height > 3-feet). Next, the contiguous vegetation areas were converted to polygons. The height value was averaged for each polygon. Then, vegetation type (*Table 3*) of each vegetation polygon was identified based on the average height of that polygon.

Water consumption of different types of vegetation considered three factors: species (ks), density (kd) and microclimate (kmc) (UC Cooperative Extension, 2000).

Water consumption difference due to species was approximated using normalized difference vegetation index (NDVI). NDVI is a spectral index for detecting vegetation greenness. It has been found to strongly correlate with vegetation water demand (Chen et al., 2015). Given this, different types of vegetation were classified into four sub-categories based on NDVI. Low NDVI indicates less water consumption, and high NDVI indicates more water consumption. The break points in *Table 4* between very low to high categories were set based on the research conducted in Tucson and desert areas (Sankey et al., 2014). Species were identified based on the average NDVI on each.

For the density factor, the amount of vegetation of the same type in a 5-meter-radius range were estimated. Density was calculated for two main classes of vegetation: groundcovers (vegetation height < 3’) and trees (vegetation height > 3’). Focal statistic rasters were created for both classes. Mean density value of each vegetation area was calculated through zonal statistics. A standardized system of evaluating vegetation density for landscapes does not exist (UC Cooperative Extension, 2000). Ranges to distinguish different water consumption levels due to vegetation density were set as 0-266, 266-531, 531-797 indicating 0-33.3 percent, 33.3-66.6 percent, 66.6-100 percent of the surrounding area covered by the same class of vegetation or vegetation polygon.

Table 3 LiDAR Classification for Species Height

Height	Vegetation type
< 6”	Contiguous area as turf
6” - 3’	Forbs and shrubs
3 - 15’	Large shrubs and small trees
15 - 40’	Medium trees
> 40’	Large trees

For the microclimate factor, the shade from surrounding buildings and trees was considered. Vegetation in the shaded area needs relatively less water. We used digital surface model (DSM) and hillshade function to obtain shaded areas for three different times of day: 9am, 12pm, 3pm. The Summer Solstice was assumed as the day used to conduct the calculation. For each vegetation area, the available shading of the three times in a day were added together to compute the microclimate coefficient (kmc). Vegetation was then classified based on the three different microclimate coefficients (kmc) levels: 0 - 100, 100 - 200, and 200 - 300, where 0 indicated vegetation covered by no shade at those three times of a day and 300 indicated vegetation was provided with entire shade coverage at all the three times.

Table 4 NDVI range for different water consumption species

Vegetation type	Contiguous area as turf; Forbs and small shrubs				Medium to large shrubs; Trees			
Species water consumption categories	Very low	Low	Average	High	Very low	Low	Average	High
NDVI range	< 0.1	0.1 – 0.2	0.2 – 0.25	> 0.25	<0.2	0.2 - 0.3	0.3 – 0.4	> 0.4

Table 5 Ks, Kd, Kmc values for different water consumption vegetation

	Species Factor (ks)				Density Factor (kd)			Microclimate Factor (kmc)		
Water consumption categories Vegetation type	Very low	Low	Average	High	Low	Average	High	Low	Average	High
Turfgrass: Contiguous area as turf	0.05	0.2	0.7	0.8	0.6	1	1.1	0.8	1	1.2
Shrubs: Forbs and shrubs	0.05	0.2	0.5	0.7	0.5	1	1.1	0.5	1	1.3
Mixed: trees, shrub: Large shrubs and small trees	0.05	0.2	0.5	0.9	0.6	1.1	1.3	0.5	1	1.4
Trees: Medium and large trees	0.05	0.2	0.5	0.9	0.5	1	1.3	0.5	1	1.4

Combining species, density and microclimate factor values, the water consumption of each vegetation area was calculated as,

T = (A*(ETL/IE))*CE*0.6233

where

T = total water consumption

A = area (sq. ft.)

KL = landscape coefficient; KL = ks*kd*kmc

ET0 = reference evapotranspiration in July; ET0 = 7.9

ETL = project specific evapotranspiration; ETL = ET0*KL

IE = 0.625

CE = Controller Efficiency; CE = 1

4.2 Residential Consumption: Indoor Water Use

Residential water use is typically expressed in gallons per capita per day (GPCD) and includes indoor and outdoor use at residences. For this study, residential water use was defined by indoor water use only (all domestic water uses other than irrigation), which includes uses such as drinking, bathing, toilet flushing, food preparation, and washing clothes and dishes. Outdoor irrigation demands were calculated separately for each township section through a methodology (see section 4.1). Water use for swimming pools was not taken into account in the outdoor irrigation computation.

Residential indoor water use was computed by using the most recent data publicly provided by Tucson Water and a recent Making Action Possible study of residential water use (MAP, 2017) where 80 GPCD was cited as the most recent Tucson residential water usage in 2015. The total 80 GPCD was split into GPCD for outdoor irrigation and GPCD for non-irrigation residential demand by using the average percentage breakdown provided in the most recent Tucson Water Annual Report for the 2014-15 time period (Tucson Water 2015), 73 percent (58.4 GPCD) for indoor use. This GPCD number was also cross checked against United States Geological Survey (USGS) national averages of domestic water use and percentage of domestic water use contributed to irrigation (USGS 2010). Each township section's residential population was multiplied against the GPCD indoor residential demand of 58.4 GPCD to calculate the daily residential indoor water demand for each township section.

5. Water Independence Model

Water independence or net zero water, on the municipal scale, is defined as an ability to supply a population's water needs with local resources. This study created a comprehensive model of the passive and active rainwater harvesting capacity within the City of Tucson to test the ability of the City to reach water independence using rainwater resources. *Figure 22* summarizes the computational components of this model.

5.1 Model Parameters Set by Exogenous Variables to Capture (Supply) and Use (Demand)

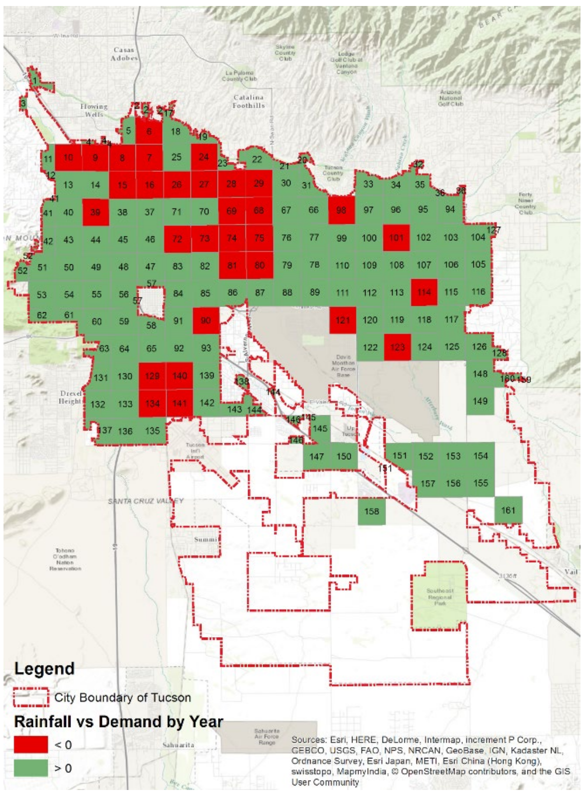
The exogenous variables of weather, catchment areas, and population distribution set the parameters of the model. Storage size was the endogenous variable responding to the limitation of operating independently from the municipal system to meet demand. Tucson's large seasonal fluctuations between months of dryness with months of wetness, variation in catchment areas (e.g. roof and street surfaces), and an uneven distribution of population and vegetation across the city create exogenous limitations on rainwater harvesting systems in Tucson. The limiting factors of the model are discussed in this sub-section, followed by a full description of the model and simulations undertaken.

5.1.1 Limiting Factor: Geographic Disparity in Demand

Areas of concentration of population or vegetation create an uneven demand for water across the City. *Figure 18* shows the 161 township sections (1x1 square miles) that comprise the City of Tucson. Many of these township sections have high demand land cover, such as golf courses.

5.1.2 Limiting Factor: Temporal Disparity in Rainfall Supply

Second, rainfall does not fall consistently over the year. Tucson experiences two discrete rain events in the Sonoran Desert (winter, day-long rain events originating off of the Pacific and summer, hour-long monsoon events, originating off of the Sea of Cortez). However, this rainwater supply does not match the fluctuation trends in irrigation and population throughout the year. *Figure 19* shows a simple comparison between rainfall supply in the month of June and irrigation and residential demand in the month of June calculated in gallons per township section.



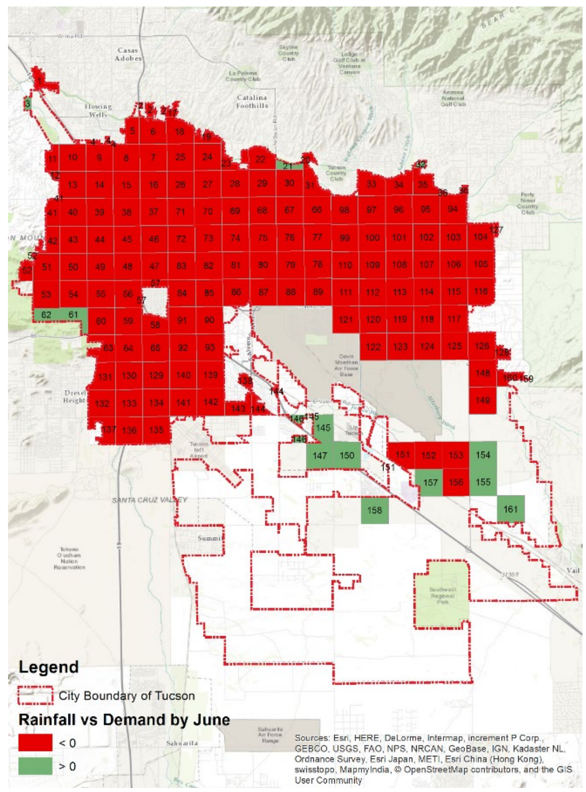


Figure 19 (left) Annual Rainwater Supply vs Water Demand (2007-16)

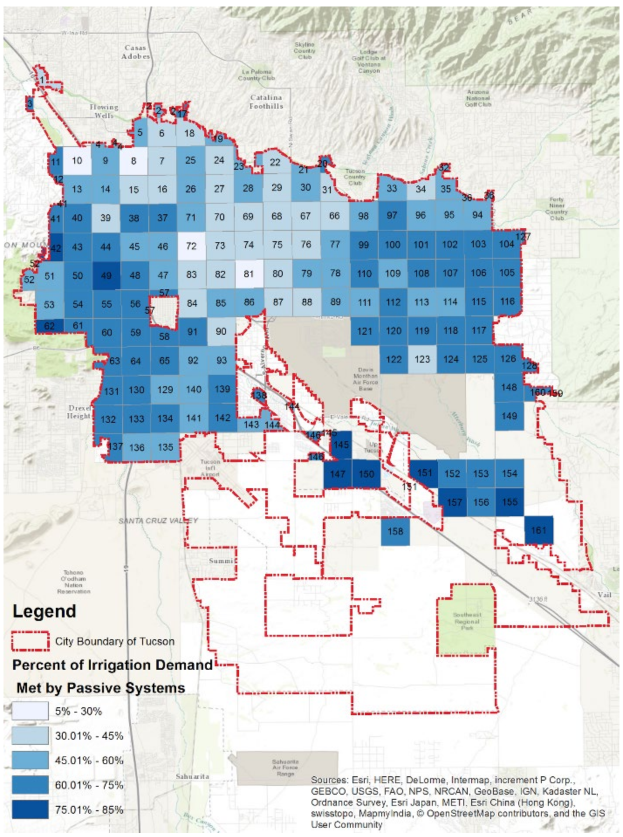
Figure 18 (right) June Rainwater Supply vs Water Demand (2007-16)

5.1.3 Limiting Factor: Passive Harvesting Catchment and No Storage

Rainwater harvesting can occur through passive (does not use storage) or active (does use storage) systems. Passive rainwater harvesting can significantly contribute to meeting irrigation needs through simply channeling water from pervious and impervious surfaces to points of irrigation demand. Localized infiltration and groundwater recharge is another important benefit of passive water harvesting. If rain falling on pervious and impervious surfaces in Tucson was designed to reach points of irrigation demand within the township section, many township sections would be close to meeting irrigation needs (see *Figure 20*). The main limiting variable with passive water harvesting is the Sonoran Desert precipitation profile of copious rain with long periods of dryness. If vegetation is non-native and unable to adapt to the dry stretches, passive water harvesting will not be successful at irrigating the species as it does not use storage. *Figure 20* shows the percentage of the monthly irrigation demand met in each township section when all rain falling on a township section's pervious and impervious surfaces is engaged in meeting the township section's irrigation demand through passive rainwater harvesting. *Figure 20* shows, that even with passive rainwater harvesting, a significant portion of irrigation demand (not to mention indoor water demand) is not met. Active rainwater harvesting is therefore necessary to achieve water independence in all township section cases.

5.1.4 Limiting Factor: Active Harvesting Catchment Size, Storage Capacity, and Pattern of Drawdown

Third, active rainwater harvesting systems depend on the daily interrelationship of the size of catchment (roof), the size of storage, and the pattern of usage of drawdown of the harvested supply. The previous sections have pointed to the variation in the pattern of usage. Catchment size also varies across township sections and causes disparities of total supply within the model. *Figure 21* displays the variation in aggregated areas of catchment in each township section.



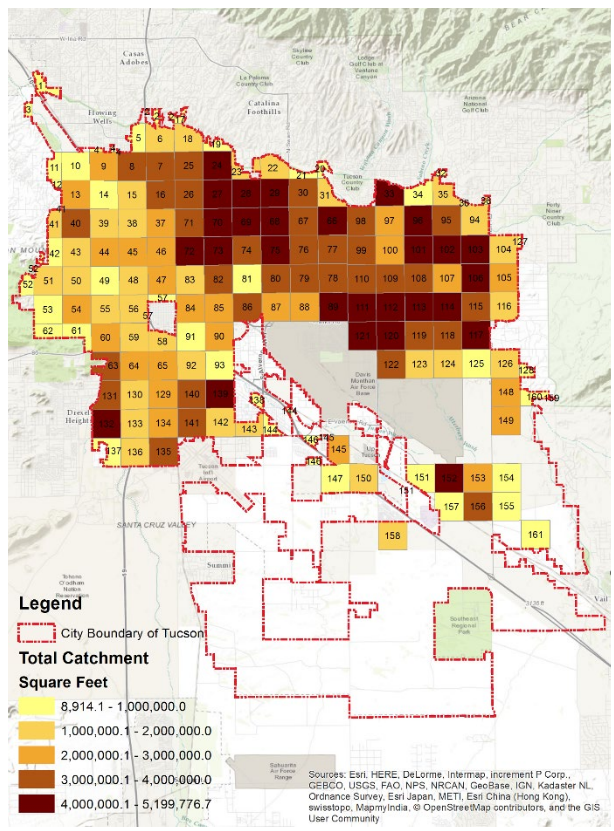


Figure 20 (left) Percent Irrigation Demand Met by Passive Rainwater Harvesting (2007-16)

Figure 21 (right) Total Roof Catchment Area (sf) by Township Section

5.2 Comprehensive Model of a Water Independent System

A comprehensive model was created to simulate the dynamics of daily passive and active rainwater capture (i.e., supply) and daily irrigation and residential consumption (i.e., demand) within the City of Tucson over the last ten years of precipitation data for this study (years 2007-16). *Figure 22* gives a summary of the computational components of the model. The model was designed to solve for the smallest storage volume necessary to reach water independence within each of the 161 City of Tucson township sections for the consecutive 10-year period. Water independence was defined as the ability to meet daily demand with daily available supply (defined in the model as *Municipal Contribution = 0*).

Two system scenarios (case 1 and 2) with a total of four cases (cases 1A, 1B, 2A, and 2B), each uniquely defining the terms of achieving water independence, were simulated and tested by the model to determine the township sections where rainwater harvesting could make the largest impact on a given definition of water independence with the least amount of required investment or smallest storage volume (defined in the model as *optimized Storage Capacity*). In rainwater harvesting systems, storage volume is the most costly element and the one that is most tightly tied to the performance of the system.

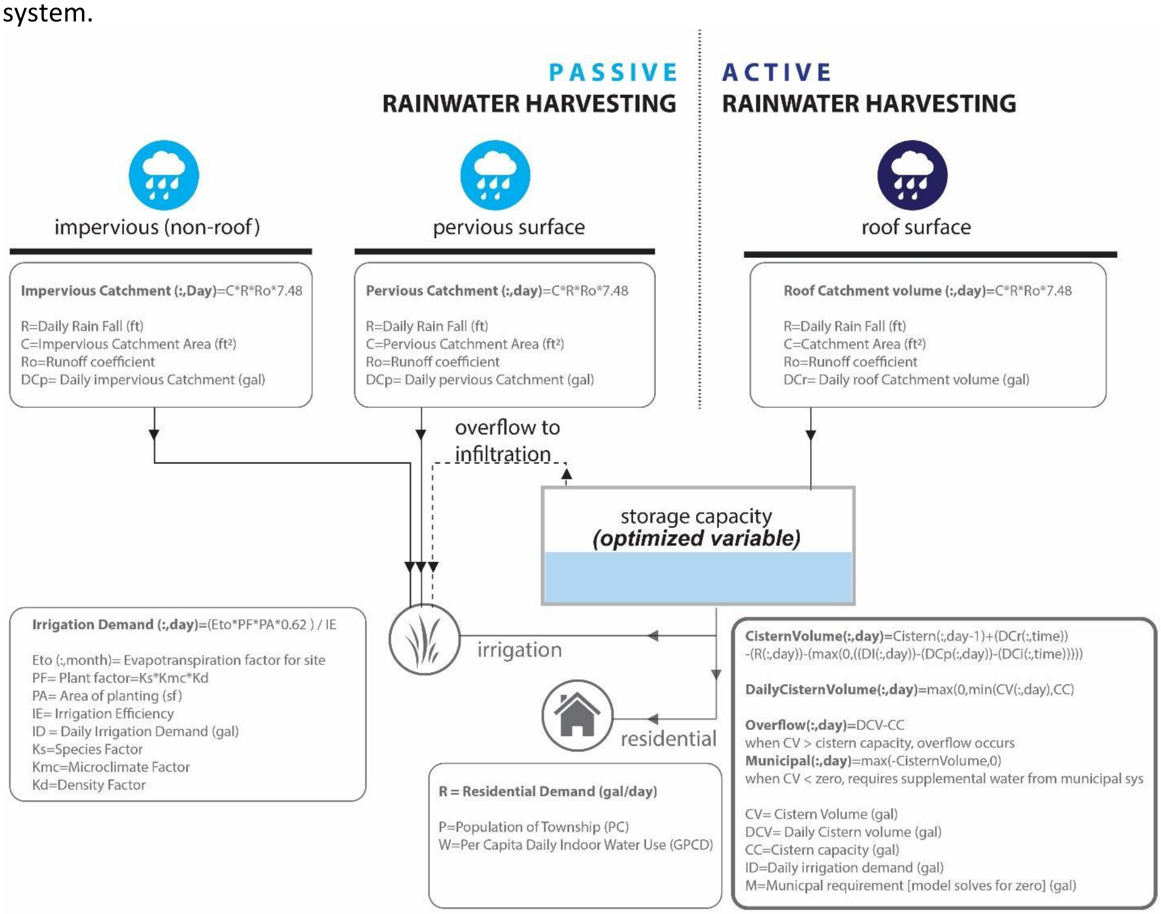


Figure 22 Comprehensive Model to Achieve Water Independence Where Storage Volume is Optimized (defined as the least amount of storage volume necessary to achieve water independence)

The following model was used where **StorageCapacity** was solved for given a zero **MunicipalContribution** in each township section:

> *day=1:3653*
> *if day==1*
> ***CisternVolume**(:,1)=**StorageCapacity**;*
> ***DailyCisternVolume**(:,1) = **CisternVolume**(:,1);*
> *else*
> ***CisternVolume**(:,day)=**DailyCisternVolume**(:,day-1)+(**RoofCatchment**(:,day)*

*-(max(0,(((**IrrigationDemand**(:,time)))-**PerviousCatchment**(:,time)*
*-**StreetCatchment**(:, day)+**ResidentialDemand**(:,day)))));*

__DailyCisternVolume__(:,day)=max(0,min(__CisternVolume__(:,day),__StorageCapacity__));
__Overflow__(:,day) = max(0,(__CisternVolume__ (:,day)-__StorageCapacity__));
__MunicipalContribution__ (:,day)=max(-__CisternVolume__ (:,day),0);

*Where **StorageCapactity** = optimized variable*
*Where **MunicipalContribution** = zero function*

6.0 Results

Results are explained through the two systems and four cases tested. Broad policy implications are then discussed.

6.1 Scenarios

This study investigated two main system scenarios to reach water independence in the City of Tucson: (system 1) a decentralized only system completely reliant on rainwater harvesting and (system 2) and hybrid centralized system (reliant on Tucson Water current sustainable wells) and decentralized system (reliant on rainwater harvesting). The hybrid system was informed by the full projected imported water need of 42 percent of total water use (from the Central Arizona Project, CAP) for the City of Tucson in 2025 (ADWR, 2012).

Within these two main system scenarios, there were four cases investigated in total:
SYSTEM 1: Complete Reliance on a Decentralized Rainwater Harvesting System to Achieve Water Independence

(1) Case 1A Water Independence: Demand = irrigation and indoor residential needs of each township section, and Supply= passive rainwater capture from pervious surfaces and streets and active capture from rooftops.
(2) Case 1B Water Independence: Demand = irrigation (met through passive rainwater harvesting only) and indoor residential needs (with a 30 percent conservation discount) of each township section, and Supply= passive rainwater capture from pervious surfaces and streets and active capture from rooftops.

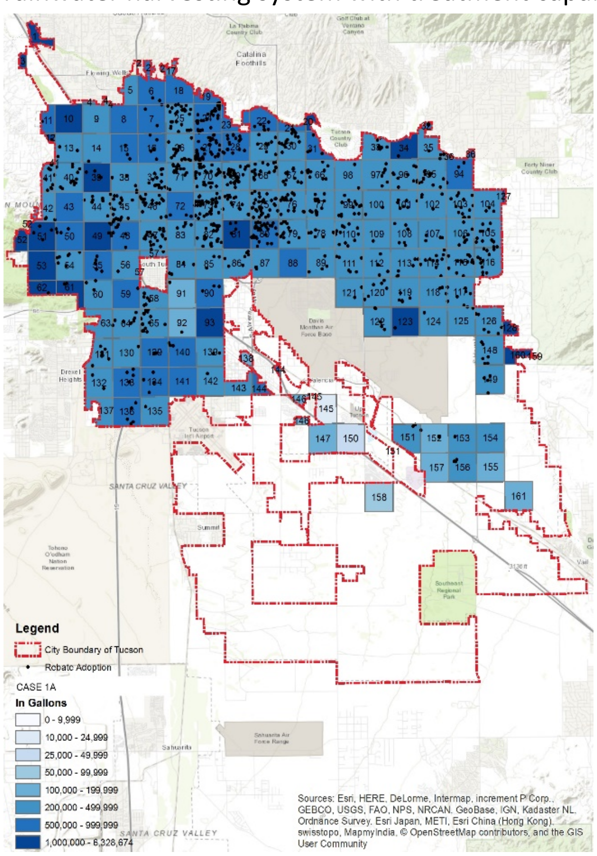
SYSTEM 2: Hybrid centralized system (58 percent current Tucson Water's sustainably managed local wells) with a decentralized rainwater harvesting system (42 percent replacing year 2025 imported CAP water)

(3) Case 2A Water Independence Defined as Replacing 2025 Projected Central Arizona Project Demand: Demand (42 percent CAP water) = irrigation and indoor residential needs of each township section, and Supply= passive rainwater capture from pervious surfaces and streets and active capture from rooftops.
(4) Case 2B Water Independence Defined as Replacing 2025 Projected Central Arizona Project Demand with High Efficiency: Demand (42 percent CAP water) = irrigation (met through passive rainwater harvesting only) and indoor residential needs (with a 30 percent conservation discount) of each township section, and Supply= passive rainwater capture from pervious surfaces and streets and active capture from rooftops.

Figures 23 and 24 display the optimized storage volumes in each township section to reach water independence in Case 1A and Case 1B. *Figures 25 and 26* display the optimized storage volumes in each township section to reach water independence in Case 2A and Case 2B.

6.2 The Most Plausible Result for Reaching Water Independence: Case 2B

Through the four scenarios, the model provides evidence that Tucson can achieve a resilient water independent system through its rainwater supplies, measured over a 10-year period. However, the financial implications of the resultant, required storage volumes make many of the proposed scenarios impractical. The results from Case 2B presented the most financially plausible option for reaching water independence. In Case 2B, Tucson's imported water supply from the Central Arizona Project (CAP) is completely replaced with harvested rainwater – passive harvesting systems meet the great majority of current estimated outdoor irrigation demands with active rainwater harvesting systems supplying indoor water demands and the remaining outdoor water needs. In this case, the storage volumes necessary to reach systems resilience is on average 10,000 gallons per 1,000 square-feet of roof area but vary over the 161 township sections. A storage capacity of 1,000 gallons required per 1,000 square-feet of roof area is the lower bound and 200,000 gallons of storage capacity required per 1,000 square-feet of roof is the upper bound (*see Figure 26)*. To make such a decentralized infrastructure intervention practical at the upper bound, significant conservation and cooperative water resource sharing between township sections would be required to lower the required storage capacity. For relative understanding, the average size of a backyard swimming pool is 10,000 gallons. A typical, domestic 10,000-gallon active rainwater harvesting system with treatment capable of reaching potable water standards costs $10,000



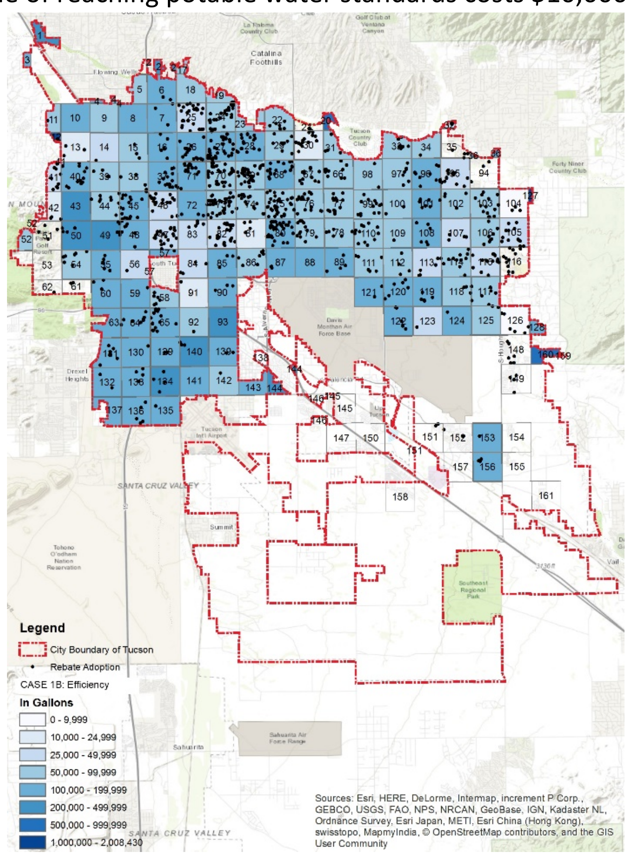


Figure 23 (left) Optimized Storage Volume for Water Independence Case 1A

Figure 24 (right) Optimized Storage Volume for Water Independence Case 1B to install (inclusive of hard and soft costs) (Texas Water, 2017).

6.2.1 The Optimal Township Sections for Rainwater Harvesting

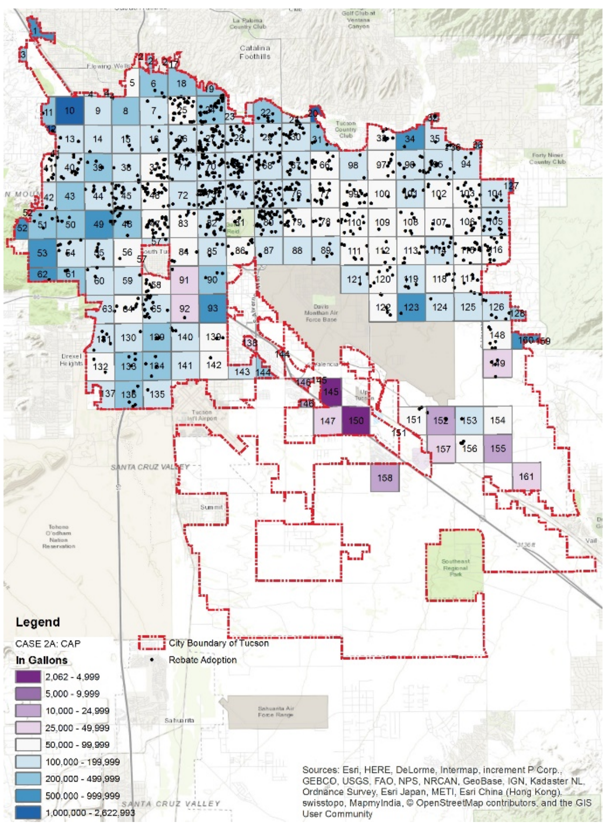
The study determined the best township sections for expanded rainwater harvesting by locating the township sections with the lowest required storage volumes to reach water independence and the township sections with the greatest potential for social return in Tucson. Case 2B provides the below results for optimal rainwater harvesting system investments.

6.2.1.1 Below 5,000 Gallons of Storage (per 1,000 square-feet of roof catchment)

In System 2, Case 2B, the township sections with the lowest storage per greatest potential for social return were **14, 18, 46, 47, 77, 84, and 92**. These township sections include El Presidio, Barrio Viejo, and adjacent to South Tucson.

6.2.1.2 Below 10,000 Gallons of Storage (per 1,000 square-feet of roof catchment)

In System 2, Case 2B, the township sections with the second lowest storage per greatest potential for social return were **9, 15, 38, 39, 58, 69, 74, and 142**. These township sections include communities along north Oracle Road and adjacent to South Tucson.



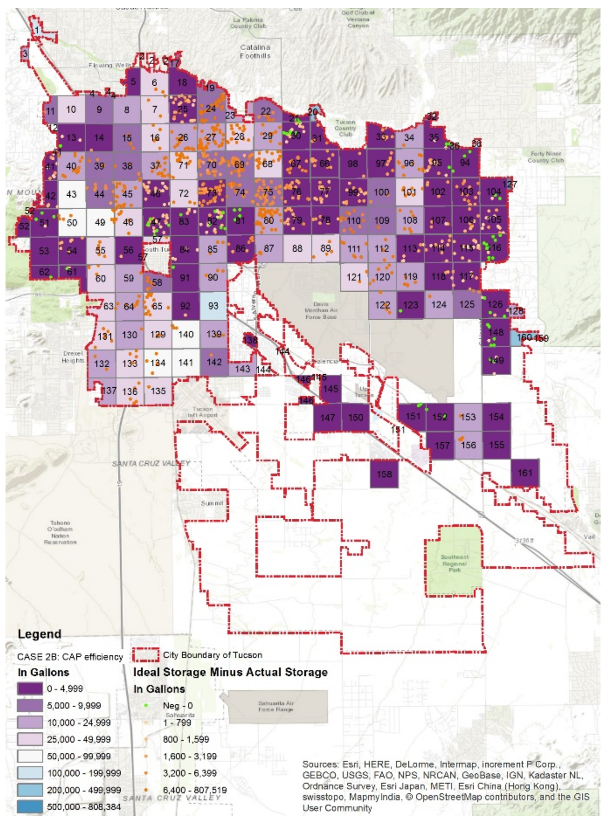


Figure 25 (left) Optimized Storage and Rebate Adopter Locations Case 2A

Figure 26 (right) Ideal Modelled Storage Minus Actual Adopted Storage Case 2B

6.3 Rainwater Harvesting System Dynamics

6.3.1 Passive Rainwater Harvesting Helps, but Active Rainwater Harvesting is Required to Reach Water Independence

Passive rainwater harvesting can address a significant portion of irrigation demand, but to achieve water independence, active rainwater harvesting is required.

6.3.2 Largest Limiting Factors

Catchment and non-native species growth were the most significant limiting factors requiring township sections to have exceptionally large required storage volume to maintain independence.

6.3.2.1 Turf Grass

In township sections where over 20 percent of land area was turf grass (e.g., golf course, public or private park, cemetery, or a culture of residential turf lawns such as in Winter Haven), water independence required storage sizes from 200,000 to over half a million gallons per 1,000 square-feet of roof catchment. Although reclaimed water currently services many of the dense turf areas in Tucson, benefits from the centralized reclaimed water system were not incorporated into the current version of the model. Future models could take into account a third system scenario where sustainably managed Tucson Water wells are used to capacity, reclaimed water is used to irrigate landscapes within the reach of the existing system, and rainwater harvesting is used to fill the remaining gap to reach water independence.

6.3.2.2 Catchment Area versus Population

In township sections where there were few buildings, active rainwater harvesting systems have little effect as the possible volume of harvested water was very small. However, when these areas had extremely low population densities and mainly native species, water independence was more practical because of the minimal water demand. However, where there was little roof area and high population (e.g., residential towers) and/or high irrigation demand (e.g., non-native species), water independence required an exceptionally large storage capacity.

6.4 Policy Discussion

In addition to expanding city, neighborhood, and household water supply resilience, rainwater harvesting has environmental, economic, and social advantages. This study used the results of its model to complete a preliminary investigation of the identified township sections where rainwater harvesting could be implemented for greatest effect and the areas of Tucson where there was the highest social return for implementing rainwater harvesting. In this preliminary investigation, highest social return was defined through (1) township sections of high poverty rate populations in Tucson and (2) township sections that had low adoption rates of Tucson Water's Rainwater Harvesting Rebate.

In a broad perspective, rainwater harvesting can be a support to high poverty communities. Communities that are able to implement significant rainwater harvesting can ameliorate flooding risk and curtail expensive infrastructure repairs. Streets that incorporate passive rainwater harvesting and yards that use active measures can increase vegetation. Greener streets offer shade which mitigates the heat island effect, improves energy efficiency of surrounding buildings, and promotes sense of place and community wellbeing. Rainwater offers a source of water which is free from increasing utility rates, and thus provides a reliable resource at a known cost to households.

6.4.1 Tucson Rainwater Harvesting Rebate Current Adoption Locations

Since 2011, the City of Tucson has offered a Rainwater Harvesting Rebate Program for the installation of rainwater catchment and reuse systems. The current site locations of the Tucson Rainwater Harvesting Rebate Adopters were overlaid with the identified optimal rainwater harvesting township sections from Case 2A in *Figure 25.* Second, the storage volumes of these adopters' rainwater harvesting systems (actual storage) was subtracted from the optimal storage from the model (ideal storage) to determine if there were current rainwater harvesting adopters in Tucson that complied with the water independence system in Case 2B in *Figure 26*. In this overlay, adopters with a negative or zero score are in compliance with the water independence system of Case 2B.

Figure 26 displays areas where rebate sites are concentrated in areas of high return and areas of high return where there is little adoption of Tucson Water's Rainwater Harvesting Rebate. One policy implication is change in the rebate structure to offer greater incentives in areas where there is greater return.

6.4.2 Tucson High Poverty Areas and Rainwater Harvesting Adoption

Since 2011, expanded rainwater use resulting from the rebate program (and the resulting environmental, economic, and social benefits from rainwater harvesting) have been localized to Tucson's wealthier neighborhoods. A notable asymmetry of access by upper income segments of Tucson has been documented. As of June 2016, close to 1,100 residents had received rebates totaling $1.44 million (Davis, 2016). The average tank size of adopters is 1,100 gallon and the maximum allowable rebate is $2,000 (Tucson Water, 2017). Of these residents, only 41 were from City Council Ward 5, which ranks the lowest in Tucson in many economic indicators, including children living in poverty and median household income (City of Tucson, 2012). *Figure 27* shows the optimal rainwater harvesting township sections identified by the model with the highest rates of poverty outlined in yellow (*Figure 6* shows overall corresponding rates of poverty in Tucson). In Case 2B, these township sections are in El Presidio, Barrio Viejo, along north Oracle Road, and adjacent to South Tucson.

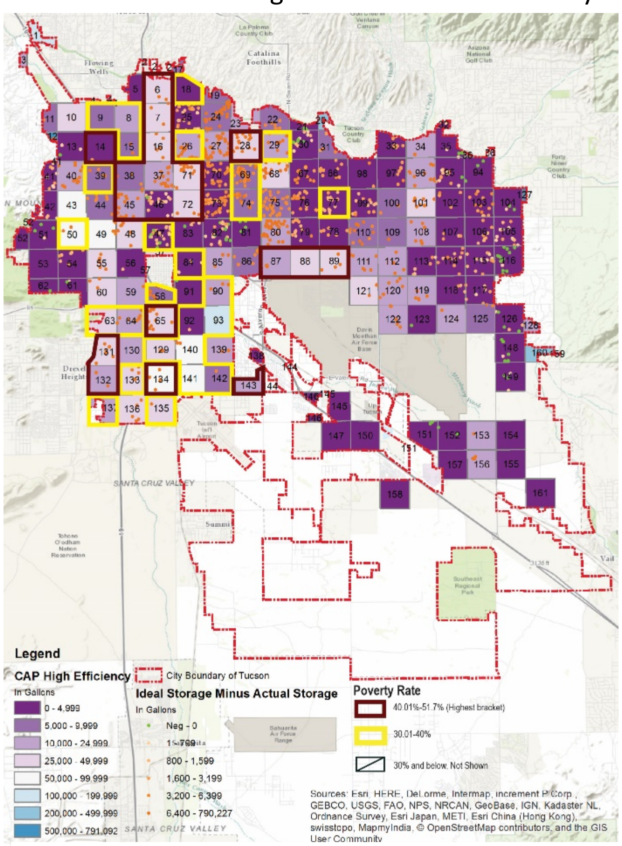


Figure 27 Optimized Storage and High Rates of Poverty Case 2B

7.0 Conclusions: Implications for Tucson's Water Future

Studies have projected that the Southwest will experience a more arid climate and higher risk of water shortages in the region over the coming century (Ault, 2016). Along with many cities in the region, Tucson is faced with a challenge: how to devise a cost effective, equitable and sustainable water supply for a growing population? What strategies can be used to realize water independence in the region? Overall, the model provides evidence that Tucson can achieve a resilient water independent system over a 10-year period through its rainwater supplies. The 10-year period model is representative of the future mega-droughts that have been projected to occur in the region by recent climate models (Ault, 2016). However, the financial implications of the resultant, required storage volumes make many of the proposed scenarios impractical. A typical 10,000-gallon active rainwater harvesting system with treatment capable of reaching potable water standards costs $10,000 to install (inclusive of hard and soft costs) (Texas Water, 2017).[4] Given the average Tucson single family's monthly water bill of $39.30 (Tucson Water, 2017), the cost of a 10,000-gallon system would take several decades to reach a simple payback.

In studies that analyze the cost of RWH systems, water price is the governing factor. Higher water prices result in shorter payback periods for systems (Morales-Pinzon et al., 2015). Zhang et al. (2009) assessed the feasibility of RWH in high-rise buildings in four cities and calculated the shortest capital cost payback period to be 10 years in Sydney. Imteaz et al. (2011) concluded that commercial buildings with large tank systems in Melbourne could achieve a 15-20 year payback of capital costs. In studies on single family homes, longer payback periods resulted. Domenech and Sauri (2011) found that homes in Barcelona, Spain had a payback period on the order of 33-43 years, depending on tank size. Across studies and countries, RWH has faster payback period when constructed at larger scales and when local water prices are higher. Although these residential numbers generally seem past an acceptable range for building projects, these models also did not consider the broader social, economic, and environmental co-benefits of RWH in their payback period analyses.

In System 1 (Cases 1A and 1B), the storage volumes necessary to achieve independence are financially impractical for citizens in almost all township sections (given current water rates and the simple payback of investing in the necessary storage volume). Although Tucson's annual rainfall volume is over 1.4 times the annual volume of water supplied by Tucson Water, the limitations of rainfall patterns, catchment area, and uneven demand create a much more difficult scenario for water independence than is apparent from simple annual comparisons. The hybrid option of System 2 (Cases 2A and 2B) offers volumes for optimized storage that begin to be more financially reasonable in many township sections. Case 2B has the most township sections with optimal storage sizes under 10,000 gallons. The most promising policy implication provided by this model are in areas of low required investment in storage and high potential societal returns (discussed in Section 6.2.2).

8.0 Future Study

The model created in this study is the first version of a comprehensive model of rainwater harvesting in the City of Tucson. There are several areas for future model refinement, scenario investigation, and additional policy implication study.

8.1 Model Refinement

1. Drought Tolerant Plants: Create a more precise model of native species ability to be drought tolerant (not require water for stretches of time). Currently, even with "very low" species factors, standard irrigation equations compute a daily water demand for species that can go for weeks without water. Future models could take into account this temporal difference between modeled residential daily demand and weekly or monthly irrigation demand.
2. Tucson Water Data by Parcel: Obtain the parcel water use data from Tucson Water to create more robust findings in the model, as the data would likely reflect effects of socioeconomic status on water use (Silva, 2016).

8.2 Additional Scenario Investigation

1. Hybrid Centralized-Decentralized System with Reclaimed Water: Create a system scenario that incorporates the use of reclaimed water to irrigate landscapes within the reach of the current system. This system would be an extension of the System 2 discussed in this study.
2. Climate Change Simulation: Study how optimized storage size changes with the projected regional changes in precipitation and temperature caused by climate change. Impacts will occur in shifts in precipitation (longer periods of dryness with more extreme rain events) and temperature (higher evapotranspiration rates). Investigate water use increases with increased temperatures and realistic potential for decreasing the lower bound of water usage.
3. Would municipal investment in large scale water harvesting be more cost effective due to economies of scale? How much would that offset future water need if recharge credits were available to stormwater harvesting efforts?

8.3 Additional Policy Analysis

Social and Environmental Impact

1. Food Deserts: How do the identified locations for rainwater harvesting maximum potential relate to the current existence of food deserts in Tucson? How could programs be targeted to encourage rainwater harvesting for re-localized food growth in these township sections?
2. Flooding: Which catchment areas in Tucson are at greatest risk for future flooding and how could subsidies target these at-risk neighborhoods?
3. Heat Island: Do areas of optimal rainwater harvesting relate to current areas experiencing high heat island intensities?
4. High Poverty Areas: Can rainwater harvesting be a resource to aid high poverty communities in addressing flood risk, food insecurity, rising water costs, and heat island intensity? How could rainwater harvesting be a support for lower incomes by providing a source of cheap and reliable water?
5. Shallow groundwater dependent ecosystems: On the urban periphery where water delivery costs more and groundwater use impacts riparian areas, how would increased incentives benefit the water resource costs and environmental benefits?

Incentive Structures for Expanding Rainwater Harvesting

6. Improved Rainwater Harvesting Incentive Structure: Could a future rebate program be tailored to sections of the city with a greater capacity (defined as minimize storage to meet demand) with a higher social benefit? Investigate how countries that have turned to private water harvesting supplies were able to achieve broad implementation.
7. Return on Investment for the Social, Environmental, and Economic Gains of Rainwater Harvesting: Given the full range of benefits from rainwater harvesting, which township sections offer the best overall triple bottom line return on investment for Tucson Water's Rainwater Harvesting Rebate Program?
8. Expand assessment to consider the rising cost of water during scarcity and the comparison of investment in water harvesting to finding other new sources of water.

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[1] Deep aquifers contain "fossil water" recharged over millennia and are not a renewable supply.

[2] The last decade of persistent drought in the Southwest has led to a drawdown of the Colorado River Basin's largest reservoir, Lake Mead, to critical levels. Lake Mead's water volume hovers near the legal level that triggers mandatory cutbacks in downstream supply to junior water right holders, such as the state of Arizona.

[3] In comparison to the non-local alternative sources of desalination or agricultural water rights trading, local alternative sources offer social, economic, and environmental co-benefits that directly benefit the local community.

[4] There may be some regional variation in cost. Although the research team is not aware of a rainwater harvesting price study completed for Tucson or Arizona, the Texas case is one of the most aligned states to Arizona.