# DETERMINATION IN-SITU RUNOFF HARVESTING (IRH) POTENTIAL OF WATERSHEDS IN ARID AND SEMI-ARID AREAS

by

**Guler Demir**

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# STATEMENT OF COMMITTEE APPROVAL

**Dr. Margaret Gitau**

School of Agricultural and Biological Engineering

**Dr. Bernard Engel**

School of Agricultural and Biological Engineering

**Dr. Gary Steinhardt**

School of Agronomy

**Approved by:**

Dr. Nathan Mosier

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# ABSTRACT

Rainwater harvesting techniques are ancient practices that have been used for many years by different countries and civilizations. Runoff water harvesting is a promising technique to collect water and store it effectively in surrounding plant or crop areas. With global warming and climate change, water availability and accessibility are becoming even more critical, particularly in arid and semi-arid areas of the world. Annual rainfall is either scarce or insufficient to support farming practices in many areas. Thus, it is necessary to capture, store, and utilize water when it is sufficient for the growing season of different crops. In this sense, it is also important to evaluate differences in watersheds in terms of determining where the water flows (runoff areas) and where it can be collected for in situ use (run on areas). Based on land use, surface types, land cover, and soil group parameters, the amount of water changes within a watershed so it is crucial to determine and combine those factors. The aim of this study is to develop methodologies for determining the runoff harvesting potential of watersheds in arid and semi-arid areas. Specifically, to: 1) Identify potential areas for in-situ runoff harvesting (IRH)within watersheds; and 2) Estimate surface runoff volumes in areas as identified. The pilot study area for this study is Winters Wash Watershed, which is a sub-watershed of Centennial Wash located in Arizona (HUC number: 15070104). This watershed serves as a proxy for arid and semi-arid areas and was selected because it has sufficient data for the planned analysis. Based on the analysis, 17,615 ha (25% of the watershed area) were classified as being suitable or highly suitable as runoff sources, while 14,092 ha (20% of the watershed area) were better suited as run on collection areas. Total collectible runoff was determined on an average annual basis. Finally, recommendations on suitable water harvesting techniques were made based on land use, soil, surface structure, and slope in the watershed. The results will provide a methodology for the decision-making process for identifying both run on and runoff areas and examples of real practices that could be used in places that are arid and semi-arid.

# 1. INTRODUCTION

To store water is particularly important during the dry season. With climate change and increasing temperatures and decreasing precipitation in arid and semi-arid areas, utilizing water for crops is a must. Rainwater harvesting refers to the practice of storing available water and utilizing it to meet different water needs such as for crops (Oweis et al., 2001). Rainwater harvesting is a very ancient practice (dating back from 4500 BC) and common across the world. Surface runoff is generated when the rainfall intensity exceeds the infiltration capacity of soil for a period of time enough to get the surface soil saturated and puddled. Surface runoff is mainly affected by soil type, soil moisture content, topography, land cover, and rainfall characteristics. Surface runoff can be captured and stored in soil or in small reservoirs such as dams and reservoirs. This form of practice is known as runoff harvesting. There are many types of runoff harvesting techniques such as negarim and contour bunds as micro catchments for runoff (Oweis et al., 2001) in which runoff is stored in-situ where it is harvested. In-situ runoff harvesting (IRH) is commonly used in arid and semi-arid areas to capture runoff and store it in the soil body for direct use by the crop. In-situ techniques are especially crucial in arid and semiarid areas as they collect runoff and keep the water in the soil. Runoff harvesting also provides recharge to groundwater aquifers and it can be easily applied in watersheds.

While determining suitable areas for runoff, there are some parameters that come into play. These parameters are highly correlated with each other, so it is important to evaluate them individually and together to create a plausible runoff map. Land use is one of the important factors in terms of determining how much water is kept on surface land. Land use distributions change within a watershed so the runoff areas can be specified based on this. While dense land cover such as croplands and herbaceous land types keep more water on the surface, barren land and fallow or idle cropland absorb less water due to not having plants on it. For this reason, it is expected that more water can be collected around plants so run-on areas can be created near plants. Crop and soil hydrologic groups are assessed together to obtain curve numbers. The surface structure is an important parameter because it identifies where water can be collected in terms of topography.

It is necessary to create a straightforward and simple systematic methodology to determine run on and runoff areas with the help of GIS. For this reason, the previous studies were used as a guide while creating a new fairly robust method to identify runoff and run on areas. In literature (Dunkerley&Brown, 1993), run on and runoff areas are described based on where water flows from (runoff) and where it gets collected (run on). These areas are characterized based on their surface structures. Identifying runoff areas is crucial because farmers need to know where water the water resources is stored to use it for farming practices.

The aim of this study is to develop methodologies for determining the runoff harvesting potential of watersheds in arid and semi-arid areas. Specifically, to:

1) Identify potential areas for IRH within watersheds; and,
2) Estimate surface runoff volumes in areas identified for IRH.

The study used the Winters Wash Watershed in Arizona (Figure 1) as a study site, which served as a proxy for arid and semi-arid areas. In this study, run on areas are defined considering surface structure as defined in the literature and crop production areas. In this sense, run on areas are where water can be collected, and crop production practices are done. So, run on areas must include both characteristics. In terms of the run  on and runoff availability, it was expected that run on areas would be accumulated around crop production areas whereas runoff areas would mostly be located in the upper and lower sides of the watershed based on surface structures.

## 1.1 Pilot Study Area Selection

This study uses the Winters Wash Watershed (Figure 1) in Arizona (HUC 1507010406) as a pilot study site. The HUC number represents hydrologic unit code and could be two to eight-digit numbers in hydrologic unit systems (https://water.usgs.gov/GIS/huc.html). This watershed serves as a proxy for arid and semi-arid areas and was selected because it has sufficient data for the planned analysis.

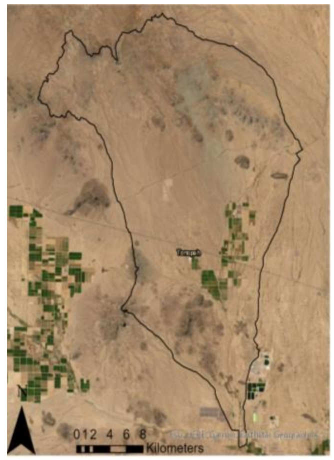


**Figure 1: Pilot study site (Winters Wash Watershed)**

The area of the watershed is approximately 710 square kilometers (274.1 square miles). Winters Wash has characteristics such as climate, land use, and landscape conditions that are representative of arid and semi-arid conditions. Considering those traits, it is appropriate for this pilot study. Average annual rainfall in this area was obtained from climate normal (1981-2010) from the state climatologist (https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8641). The most and least amount of rainfall observed are typically in June (0.04 inches, 1.01 mm) and August (1.10 inches, 27.94 mm), respectively. Maximum temperatures occur in July (106.9 $^{o}$F, 41.6 $^{o}$C), while the lowest temperatures are experienced in December (37.5 $^{o}$F, 3.05 $^{o}$C).

The shrub is the main land use type within the watershed (80%), followed by herbaceous (13%) and cultivated crops (4%) and barren land (3%) based on 2016 National Land Cover Database(NLCD) land use (https://www.mrlc.gov/ ). Alfalfa/Hay is the main crop within crops (33%) and other crops such as grains, cotton, double crops and, vegetables occupy around 32.6% of the land use-area based on the 2016 USDA Crop Data Layers (https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php). The watershed is mostly flat with some concave and convex structures on the upper and lower side.

# 2. LITERATURE REVIEW

## 2.1 Runoff Harvesting

There are several factors should be taken into consideration for runoff harvesting practices. These include climate, topography, land use/land cover, soil and plant characteristics, hydrology, and socioeconomic conditions (Oweis et al., 2012). Climate is a crucial factor because it has a direct impact on temperature and rainfall. Topography has an impact on flow direction and flow accumulation, so it should be used as a criterion (ETWWA, 2010). Land surfaces that have a lake at the bottom and draining location are a desirable topographic feature for Runoff Harvesting Techniques (Frasier&Meyers, 1984). Soil is important in terms of infiltration rate and water holding capacity because it affects the amount of runoff to be captured; medium-textured (loamy) soils are determined to have the best suitability for water harvesting techniques (Matlock&Dutt, 1986). Given the variety of important factors, it is necessary to determine areas that are suitable for implementing runoff harvesting techniques. The scope of this study is to determine climate, soil types, land use, topography, and watershed runoff to reveal potential areas for runoff harvesting.

For soil and water systems, it is important to protect the land from degradation by rehabilitation of the land and vegetation cover (Alemayahu et al., 2008). Runoff coefficients are specifically affected by land use (Dhakal, 2012).

## 2.2 Identifying Suitable Areas

There are some major studies conducted in arid and semi-arid areas in the world to identify suitable areas for water harvesting practices. One of them is in Kiambu County, Kenya (Mugo &Odera, 2019) based on the geospatial approach. In the study, water harvesting structures were developed for potential runoff water harvesting. The Shuttle Radar Topography Mission (SRTM), global digital elevation model (GDEM), and Landsat 8 were used in the ENVI 4.7 environment, and for other thematic layers, ARCGIS was used for the determination of potential rainwater harvesting areas. The Soil and Terrain Database for Kenya (KENSOTER) soil database and Tropical Rainfall Measuring Mission (TRMM) were also used to classify soil groups and calculate annual rainfall, respectively (Mugo&Odera, 2019). The SCS-CN method runoff generation technique was used to integrate land use cover and hydrologic soil group layers to determine runoff depth. For this area, there were two solutions to solve the water shortage problem. In this study, there were two main approaches adopted with the first being the technical design of dams and the second identification of suitable areas. Thus, the suitability model implemented in ArcGIS 10.2 was used to create suitability maps. The model was combined with various factors including areas, slope, runoff depth, land use, soil texture, and stream order. With this method, high potential areas were identified for water harvesting techniques.

Another study was conducted in Taiwan. The study aimed to convert a railway station system based on spatial data to manage rainfall data appropriately (Cheng&Liao, 2009). In the study, rainfall data were clustered based on a hierarchical 2 step cluster process so that regions with similar rainfall characteristics were found. Another study was conducted in Taunton River Watershed in Eastern Massachusetts, USA. In the research, distributed parameters including runoff coefficients, land use, soil properties, precipitation, aquifer, and land price were used in the analysis (Sekar&Randhir, 2007). The approach of the study was based on land use, soil data, groundwater potential, and economic cost assessment. In conclusion, it is determined that the areas which have the potential for water harvesting techniques are dispersed in the eastern parts of the watershed using a spatial data approach to install water harvesting structures (Sekar, 2007). The author concluded that subsurface and groundwater should potentially be evaluated together. Another study was run in two different regions in the Makanya watershed, Kilimanjaro Region, Tanzania (Tobo, 2005). Based on slope steepness and soil types, areas were determined for which a specific kind of water harvesting technique should be used. The results were tested in a Decision Support System (DSS) in terms of the technique’s suitability for the areas.

Another research effort was done in Kali Rivershed, Mahi River Basin in India (Ramakrishnan et al., 2009). In this study, a spatial approach was used to assess water harvesting structure suitability. The parameters considered potential runoff and slope factors.  The decision tree approach was used in this study using GIS (Ramakrishnan et al., 2009). A study was carried out in the Alaba District, Ethiopia with the objective being to assess the impacts that water harvesting technologies would have on water availability downstream. To analyze the hydrological impact, the Soil and

Water Assessment Tool (SWAT) model was used (Seka et al., 2015). It was noted that in the study, water harvesting technique success depended on the technical design and identification of suitable sites. High potential areas for water harvesting techniques were identified using a suitability model. The model was created in Model Builder in ArcGIS 10.2. and considered several different factors, including slopes, runoff depth, land use, soil texture, and stream order.

A case study was applied in the upper Geba watershed in northern Ethiopia (Grum et al., 2016). In the study, participants who had local and scientific knowledge chose the most suitable sites for Runoff Harvesting Techniques at the first step. Later, a GIS-based multi-criteria analysis approach was used as a selection criterion. The results of the analysis were shared with the stakeholders in a workshop. An ultimate selection based on multi-criteria analysis was compared with the anticipated results so that the multi-criteria approach was verified. The multi-criteria approach had a validation of 90% and 93% with existing check dams and percolation ponds, respectively (Grum et al., 2016).

The research was done in Jordan using three approaches to evaluate the suitability of RHT intervention. The researchers took biophysical criteria and used a GIS tool for the suitability analysis. They developed a system to identify the land suitability for different types of water harvesting techniques at the watershed level (Ziadat et al., 2006). In another study, the SWAT model was applied to determine current and future water availability in the NR4 reservoir. The study was carried out in Oahu, Hawaii. In the study, the climate change effect was determined in reservoir NR4. In their study, the SWAT tool was adequate to represent daily streamflow hydrographs for all stations. This study is important because it provided water harvesting scenarios for the Pacific and other islands in the future (Leta et al., 2017).

A study was carried out in the Kakareza watershed in Iran. The objective was to determine the watershed suitability for water harvesting techniques, especially for farm ponds. Two main methods which are Analytic Hierarchy Process (AHP) and Weighted Linear Combination (WLC) were used to utilize spatial maps in GIS (Karimi&Zeinivand, 2018). A study was carried out in Malawi on rainwater harvesting techniques to diminish the scarcity risk in maize (Zea mays L.) production. For this study 5 soil types and 12 rainfall regimes were used to model the effect of tied ridging on soil water using the water balance model TIEWBM. Results showed that tied-ridging could potentially benefit the crop where soils were fine-textured and in areas with seasonal rainfall between 500–900 mm during drought or dry years.

A study was performed to assess water harvesting applications in Greece. The work area was chosen considering the existence of cropland areas in the specific region. Aspect, slope, soil type, vegetation, temperature, and precipitation were also considered in the study. The soil of the area was determined as clay to clay-loamy texture. As a result of the study, it was determined that precipitation through the year was extremely uneven, and it fell between May-September. The infiltration capacity of the soil was also estimated (Elhag&Bahrawi, 2016).

Another study was carried out in India. The study differentiated from the past studies in terms of its approach to prioritizing areas for RWH and recharge structures. The study used field measurements and remote sensing data obtained from different government agencies; The soil map was generated by India's National Bureau of Soil Survey and Land Use Planning (NBSS&LUP); meteorological data were obtained from India Meteorological Department; slope and drainage density maps were also created. Since monsoons are a very important factor for the area, pre- and post-monsoon groundwater levels were taken into consideration. Results of the study showed potentially suitable zones for water harvesting techniques using runoff coefficients, slope, and drainage density maps (Singh et al., 2016).

## 2.3 Estimating Surface Runoff

Surface runoff water is crucial for groundwater recharge and downstream water levels. There are many publications on how the land use change over time affects surface runoff. Leopold (1968), American Society of Civil Engineers (1969), Dunne and Leopold (1978), and Walesh (1989) proved that more impervious areas meant more surface water (Harbor, 1994). Surface runoff was calculated using Soil Conservation Service Curve Number (SCS-CN) developed by the United States Department of Agriculture (USDA, 1986). This method is based on the water balance equation and two fundamental hypotheses (SCS 1956). The curve number method equation empirically represents the relationship between runoff, rainfall, potential maximum retention after runoff begins, and initial abstractions. All abstractions in this equation are lumped into the threshold depth value. This value is a subtracted value from total rainfall to calculate runoff volumes. In other words, precipitation value must exceed the threshold depth value for runoff generation. The reason to use the curve number method in this study is that in situ runoff estimation depends on the land cover, hydrologic soil structure, antecedent soil moisture, and precipitation. Curve number is a strong method to cover all of these factors in the same equation.

a) Water balance equation to an individual storm is,

$$P = Q + L$$

$P = Precipitation,$ Q=surface runoff(also rainfall excess), L=losses or hydrologic abstractions

In arid and semi-arid areas, water harvesting techniques provide alternatives to capture the water and utilize rainwater runoff efficiently. In this way, the available water can provide a sustainable agricultural environment. The human population is increasing and water is crucial (Ziadat et al., 2006). To find the potential of watersheds with high accuracy is important considering climate change and farming activities in terms of utilization of runoff waters in these places. Runoff is described as a flow of a water layer over the land surface into the soil pores and sediments that are coming out from watersheds. Three types of runoff are described 1) rainfall-runoff, 2) direct runoff, and 3) surface runoff (Lii &Vereecken, 2019). The classical model of surface runoff is related to soil infiltration capacity and rainfall. This is called infiltration excess runoff (Lii&Vereecken, 2019).

With respect to runoff estimation, the HEC-HMS model was used to simulate the rainfall-runoff process in Balijore Nala Watershed of Odisha, India (Choudhari et al., 2014). Other research was done in Cairo Egypt. The potential runoff was estimated by using Finkel-SCS rainfall-runoff methods (Elewa et al., 2012). Another study was carried out in South Korean watersheds. Runoff estimation was carried out using the calibrated CN (Ajmal et.al., 2015). One study was aimed at collecting runoff water and nutrients from small rocky watersheds, into ponds which are used as an afforestation grove. There were two indicators used in this study to determine runoff harvesting efficiency: soil quality (SQ), and aboveground net primary productivity (ANPP). The study was carried out on four small watersheds in the Negev Desert, Israel. The study showed that using

Runoff Harvesting Systems (RHS) can be an essential technique for a sustainable and natural ecosystem by increasing soil quality and productivity in the limans (Kagan et al., 2017).

Another study carried out in a Mediterranean Watershed used the Annualized Agricultural Non-Point Source (AnnAGNPS) model to estimate event runoff, peak discharges, and sediment loads (Zema et al., 2015). Other research was carried out in Tunisia, in Wadi Oum Zessar Watershed. The soil profile of the research field was sampled to determine soil texture and water retention curves. Average monthly rainfall data was also obtained. The runoff was determined using the time compression approximation (Schiettecatte, 2004). A case study was carried out in eight watersheds in Iraq. Runoff from the study areas was estimated by using regressions equations. Several models were found suitable depending on study site location and other characteristics including average elevation, average annual precipitation, and slope of the mainstream. Based on the results of the study, a reservoir was proposed (Rahi et al., 2019).

### 2.4 Determining Available Water Storage (Available Water Capacity)

Field capacity and the permanent wilting point are two factors to determine available water storage in the soil. The soil at field capacity is full with water that can hold against gravity, while Permanent Wilting Point represents an important index for plants that plants cannot access the water due to the soil dryness (Lopez&Barclay, 2017). According to the United States Department of Agriculture, available water storage or available water capacity is the amount of water that soil can hold for the use of plants (https://www.nrcs.usda.gov/wps/portal/nrcs/site/soils/home/). To have better water need estimation, we will be using available water storage for both run on and runoff areas. In this study, run on areas are defined as water sink zones, while runoff areas are defined as water sources (Dunkerley &Brown, 1993). The upper layers of the soils are penetrated by roots, those roots absorb stored waters for transport from roots to upper portions of the plants. Available water is used by plants as vapor or liquid form. Field capacity means the water is captured by the upper side of the reservoir, and the water held at the lower side of the reservoir is a permanent wilting point. The difference between those two limits of reservoirs is referred to as soil available water capacity. Available water capacity presents the available water for plants (Cassel&Nielsen, 1986).

Milly (1994) expressed that the available volume of water for roots was not certain. However, this considered all soil up to the maximum root depth, which was about 1 meter. The effective storage would then be 0-15 cm. It is proved that land use change over time affects water quantity within watersheds by different researchers (Calder 1992, Fohrer 1999). Available water storage is used as a parameter because it is critical for surface runoff that can be stored. More water stored in the soil means more moisture in the soil surface and less water retention. More saturated or moisture in the soil provides more runoff than the unsaturated soil types in the same precipitation conditions. Less available water storage means less water can be stored.

### 2.5 Determining Suitability

In this study, we propose a different and practical approach compared to previous works. This approach includes spatial variability, and combining all important factors in terms of runoff and run on potential in GIS. While previous studies only focused on runoff suitability, here we proposed a merged approach that considers run on areas in terms of availability and the amount of water that can be collected from runoff areas. There are different approaches to determine the suitability criteria. With the practicality and easiness to work with geospatial data (GIS use), we chose a GIS-based approach. In order to do that, each factor considered was scored from 1 to 5 using a raster data format. The values from 1 to 5 were chosen so as to obtain a meaningful output that is easy to interpret. This also allowed meaningful levels of suitability to be defined (Table 1).

**Table 1: Assigned classification (rankings) of suitability scores from 1 to 5 for different parameters**

| RANKING | SCORE |
|---|---|
| High suitability | 5 |
| Moderate suitability | 4 |
| Low suitability | 3 |
| Very low suitability | 2 |
| Unsuitable | 1 |

# 3. MATERIALS AND METHODS

## 3.1 Watershed Characterization

The Winters Wash land use map was classified using its land use, land cover, surface structures and, soil parameters. Land use data were reclassified in the ArcGIS Pro environment according to the main land use types. Reclassification was based on regrouping similar land uses under one group. This was necessary to make the ranking process smoother. According to the land use data, shrub (scrub), herbaceous, cultivated crops, and barren lands were classified individually, while Developed, Open Space/Developed, Low Intensity/Developed, Medium Intensity/Developed, and High Intensity/Developed were reclassified as “Developed”. Open Water, Woody Wetlands, Emergent Herbaceous Wetlands were also classified under one category Wetlands. Hay and Pasture were also classified as a separate group Hay and Pasture. Land cover was also classifed based on crop types cultivated within the watershed. In this classification, alfalfa, other hay, and nonalfalfa weres classified separately from other crops in the watershed in one group, and fallow/idle and barren cropland were combined as one group The remaining layers are grains, and cotton, developed, and wetlands were left as they were in the land use classification. Unique value symbology types were assigned to both land use and land cover since it is more distinctive for the reclassified data.

### 3.1.1 Topography

As an indicator of topography surface structures and slope layers were created. Topography has an impact on concave, convex, and flatness in the watershed. This affects where the water can be collected or obtained. The topographic structure was created by using a Digital Elevation Model (DEM) and DEM map as inputs to the curvature tool. This tool values change from -9 to 12 (negative values indicate concaveness and positive values indicate convexness). The reclassify tool was used to determine the surface structure map. The natural breaks method was used to create a topography map because this method uses non uniform distributions, and surface structure shows a non-uniform distribution type within the watershed.

### 3.1.2 Soil

#### 3.1.2.1 Available Water Storage

Available water storage was used as the score parameter because this parameter is critical for crop growth, and it gives us information on how much water would be available in the soil for plant use. Storage of soil moisture can be grouped into two moisture classes. Those held between saturation and 0.3-bar tension and between 0.3 bar tension and 15-bar tension (field capacity). The 15 bar- tension moisture is called *wilting point* and represents the minimum available water that can be taken by plants (Novotny&Olem, 1993). After obtaining soil data from USDA: NRCS Geospatial Data Gateway (https://datagateway.nrcs.usda.gov/), the data were taken representing the 0-100 cm depth as weighted average data (aws0100wta). This was used to create soil scores. Null values were found for flooded and gravel/borrow pit areas that are covered by water. The null values were replaced with the largest number after zero in the data because null values would not be suitable for the analysis process. Available water storage values ranged from 1.05 to 20 bar/centimeter. Higher available water storage was ranked more favorably for run on and less availability for runoff scores.

#### 3.1.2.2 Saturated Hydraulic Conductivity of Soil (Ksat)

Saturated Hydraulic Conductivity of Soil (Ksat) is the infiltration rate once the ground has reached 100% saturation and the infiltration rate has become constant. From USDA-NRCS soil data, the Ksat (representative) column was utilized. The Ksat values ranged from 0.91-141. The natural breaks method was used to derive 5 classes representing hydraulic conductivity, ranging from 1 (unsuitable) to 5 (high suitability). The scores were assigned by considering how quickly the water is transmitted downward within the horizon. In this case, as Ksat values increase runoff suitability decreases.

#### 3.1.2.3 Threshold Depth Value

Thresdold depth is a parameter that represents the amount of initial abstraction and total infiltration. Initial abstraction depends on land management and land use condition, interception, infiltration: depression storage, and antecedent soil moisture. According to the empirical statistical relationship, this value is obtained through the multiplication of the volume of storage with a 0.2 constant number ((Novotny&Olem, 1993). The Curve Number method is used to calculate the threshold depth value. To determine unique soil and land use combinations based on which to assign curve numbers, the method documented in Gitau (2003) was applied using the raster calculator in ArcGIS Pro. Two different parameters (land cover and hydrologic soil group) were considered to determine the curve number to calculate the threshold depth value (Equations 1 and 2).

$$\boldsymbol{S = \frac{25400}{CN} - 254} \text{ ..................................................} \textbf{Equation[1]}$$

$$\boldsymbol{D_T = 0.2S} \text{ ...........................................................} \textbf{Equation[2]}$$

Where: CN is the curve number; S=Potential maximum retention after runoff begins. S is multiplied by 0.2 to obtain the threshold depth value ($\boldsymbol{D_T}$).

## 3.2 Calculating Overall Suitability Scores (Geometric Mean)

To calculate the overall suitability score, all the characteristics described were considered using the ratings 1-5 as described in the previous section. All the given scores were merged in the raster calculator (Equation 3). The geometric mean was used as the final calculation method to obtain suitability maps because it is more resilient to the marginal values in the data. Since some of the parameters do not fit a normal distribution, the geometric mean is a better approach compared to the arithmetic mean. A geometric mean is advantageous to use because it is less affected by extreme values in a skewed distribution (Cater, 2010). The sample geometric mean (SGM) introduced by Cauchy in 1821, is a measure of central tendency that is widely applicable (Vogel, 2021). Several studies have used geometric mean for final suitability analysis. For example, Tahvili et al. (2021) used a combined approach including geometric mean to determine rainwater harvesting locations. Singh et al. (2017) used a geometric mean to weigh thematic layers as a comparison to find water harvesting potential. In this study, land use/land cover, surface structures, available water storage, soil hydraulic conductivity, and threshold depth value scores were taken into consideration. To calculate the geometric mean, first, all scored parameters were extracted as individual layers using the reclassify tool. Later, the raster calculator was used to calculate the geometric mean from the five parameters.

$$Score\ \left(\prod_{i=1}^{5} X_i\right)^{\frac{1}{5}} \qquad \text{(}\mathbf{Equation\ 3}\text{)}$$

Where: $X_1$= land use $X_2$=surface structure….. $X_3$=available water storage $X_4$=soil hydraulic conductivity $X_5$=threshold depth

### 3.3 Suitability Map for the Study Watershed.

The suitablility map was plotted based on the scores calculated using Equation 3 and based on the suitability for run on and runoff areas. After the map was plotted based on the suitability levels, unsuitable very low and low suitability areas were reclassified under one level so the suitability map gave a better picture (more readily interpreted) in terms of suitability areas.

### 3.4 Calculating Runoff Volumes from Identified IRH Areas.

Within the watershed, there is only one station with weather data: Tonopah, Arizona (lat/long: 33.4204, -112.86). Tonopah has data from 1951-2010 but has many missing values. In this study, only the data from 2004-2010 was used since the aim was to calculate average annual values from recent years. However, from 2004-2010 most of the years were missing precipitation and maximum and minimum temperatures. The data availability for all these parameters is shown in Table 2.

**Table 2: Precipitation data availability for study watershed**

| Years | Complete | Incomplete |
|---|---|---|
| 2004 | 6 months | 6 months |
| 2005 | 10 months | 2 months |
| 2006 | 12 months | - |
| 2007 | 11 months | 1 month |
| 2008 | 12 months | - |
| 2009 | 12 months | - |
| 2010 | 7 months | 5 months |

As shown in Table 2, only 3 years (2006, 2008, and 2009) had complete data and the rest of them were missing. To achieve objective 2, as a first step precipitation data needed to be generated. To obtain precipitation values, the LARSWG weather generator (https://sites.google.com/view/lars-wg/ ) was used. LARSWG is a stochastic weather generator that is widely used by different researchers around the world.

In this study, 25 different precipitation outputs were generated based on the literature (Guo et al. 2017). From these 25 outputs (Runs 1-25), the annual total rainfall was compared with the original values from complete data in the Excel environment. Run 8 was found to be the closest one to the original annual summation of rainfall, so Run 8 became a possible simulation to use in the next computation steps. After this step, rainfall totals for each month in each year for Run 8, original complete data, and climate normals obtained from the Arizona State Climatologist (https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?az8641) were obtained. Then, averages for each month, e.g. average computed from all January(s), etc. were compared among the three datasets. The difference among climate normals, original data, and generated data (Figure 2) was at most 16 percent. Thus, it was considered sufficient to proceed with runoff calculations using Run 8.

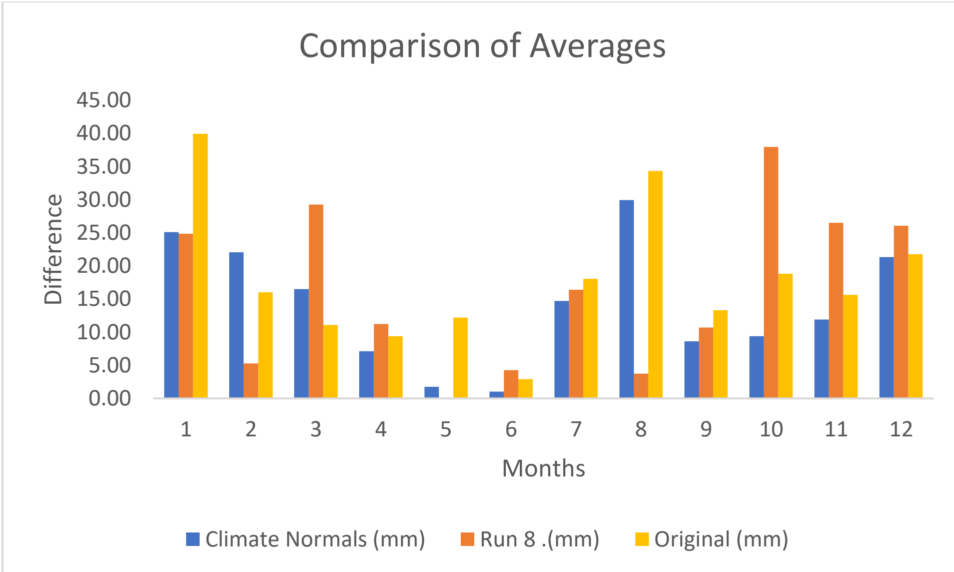


**Figure 2: Comparison of simulated rainfall (run 8) with climate normal and original data**

Runoff volumes were obtained using the curve number method

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \qquad \textbf{(Equation 4)}$$

Where: Q= runoff(in); P = rainfall(in); S =potential maximum retention after runoff begins (in)

# 4. RESULTS

In this section the scores obtained are shown in tables. For the easiness of reading maps, all maps are provided in one figure (Figure 3).

## 4.1 Results of the Characterization

### 4.1.1 Land Use

From 2016 Winters Wash watershed land use data, the watershed consisted of 76% Shrub/Scrub, 13% Herbaceous, 5.3% Cultivated, 1.3% Hay Pasture, Open water, Developed areas from low density to high density, barren land, deciduous forests, and wetlands occupied 4.4%. According to the percentages of the land use, it can be concluded that the watershed is mostly shrub (76%). The developed areas constitute a small portion of the watershed. This is a crucial factor in terms of determining curve numbers for any hydrologic model used. Computed scores for land use are shown in Table 3.

**Table 3: Assigned land use scores for both runoff and run on areas for different land use types**

| | Runoff Areas† | | Run on Areas† | |
|---|---|---|---|---|
| **Land use types** | **Scores** | **Interpretation** | **Scores** | **Interpretation** |
| Developed open space | 5 | High suitability | 1 | Unsuitable |
| Barren land | 4 | Moderate suitability | 2 | Very low suitability |
| Shrub/Scrub | 3 | Low suitability | 3 | Low suitability |
| Herbaceous | 2 | Very low suitability | 4 | Moderate suitability |
| Other land use types | 1 | Unsuitable | 5 | High suitability |

The land use has an impact on water retention on the surface. In most studies, it was found that there is a strong correlation between surface runoff and urbanization (Chen et al 2011) (Ali et al. 2011) (Hernandez et al 2000). According to a study, the HEC-HMS model simulated increased runoff with increased urbanization (Ali et al. 2011). Here, we defined five important land use groups in terms of an area that they take; urban and barren spaces are the landscapes that could produce most of the runoff within the watershed. More vegetation indicates less runoff due to the capture of different sorts of plants. For these reasons, shrub herbaceous and other land use types were given values of 3, 2, and 1, respectively, while developed and barren lands were assigned 5 and 4 as suitability scores. In other words, while we can get desired runoff from developed and barren lands for the purpose of this study, we can not get the desired amount of runoff from spaces that are covered by any kind of vegetation and plant.

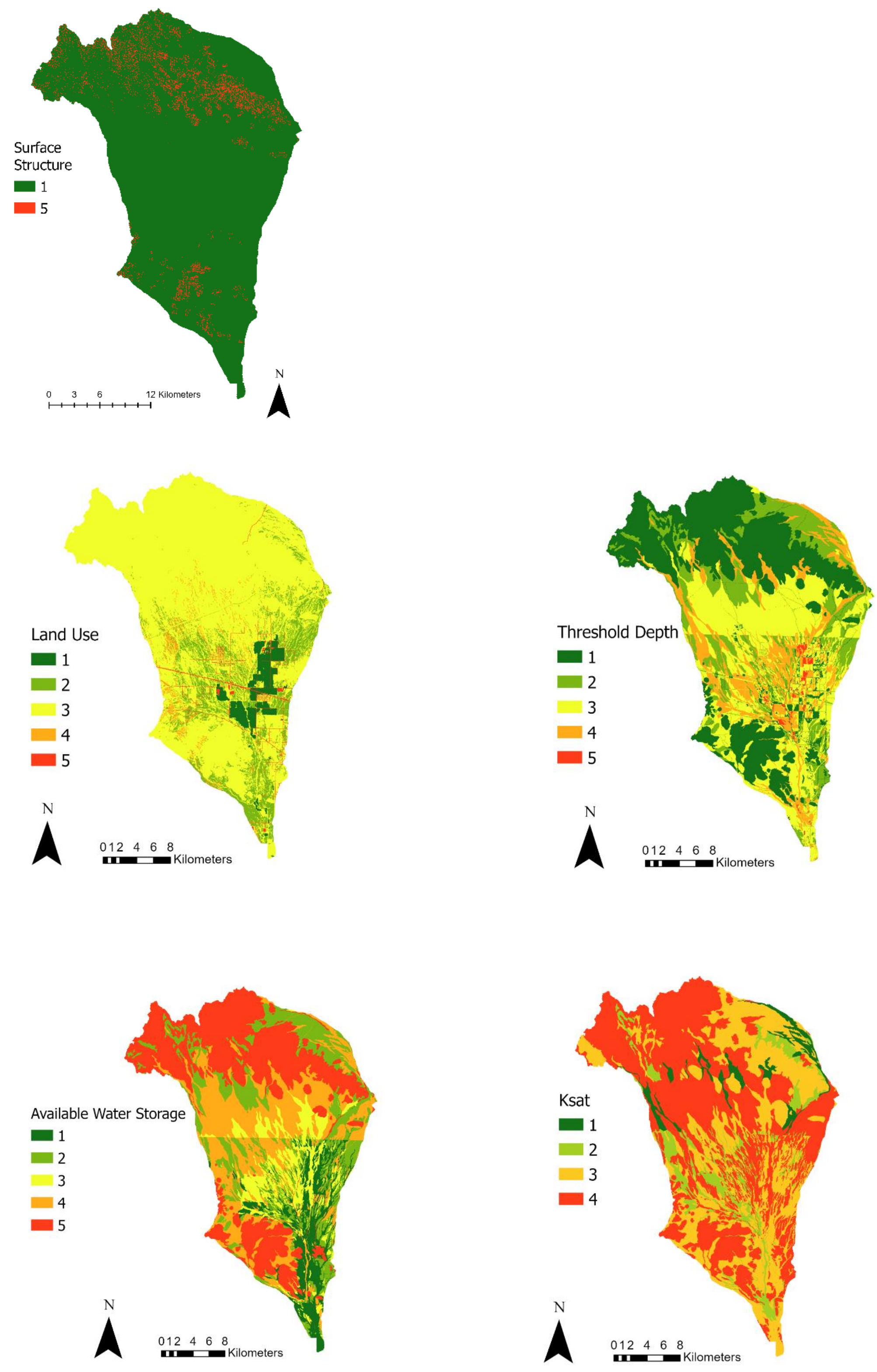


**Figure 3: Suitability scores for key factors considering potential areas for runoff in the winters wash watershed**

### 4.1.2 Topography

The watershed is mostly flat with some concave and convex strrutures (Table 4).

**Table 4: Assigned topography scores for both runoff and run on areas for concave, convex and flat areas**

| | Runoff Areas† | | Run on Areas† | |
|---|---|---|---|---|
| **Topography** | **Scores** | **Interpretation** | **Scores** | **Interpretation** |
| Concave | 5 | High suitability | 1 | Unsuitable |
| Convex | 5 | High suitability | 1 | Unsuitable |
| Flat | 1 | Unsuitable | 5 | High suitability |

Vivoni et al. (2004) suggested that a basin's spatial variability has an impact on soil moisture and runoff generation with a clear shift toward concave basins. Bedrock depth, channel density, and such factors are also associated with the topography and surface runoff relationships. In this study, the values for topography structures are assigned based on where water moves and where it can be collected. According to this, the assumption is concave and convex structures are potentially the high suitable areas where runoff is created along the surfaces due to the elevation factors. Flat topography structures are assumed where water is accumulated, so these areas are not suitable for run on.

### 4.1.3 Soil

#### 4.1.3.1 Available Water Storage

Available water storage map ranges from 1 to 5 based on scores. This means 1 is unsuitable for runoff areas, whereas 2 is very low suitability, 3 represents low suitability, 4 moderate suitability, and 5 high suitability for runoff areas (Table 5).

**Table 5: Available water storage suitability scores for runoff and run on Areas for different range of values**

| | Runoff Areas† | | Run on Areas† | |
|---|---|---|---|---|
| **Range of Values** | **Scores** | **Interpretation** | **Scores** | **Interpretation** |
| 1.0–4.5 | 1 | Unsuitable | 5 | High suitability |
| 4.6–7.9 | 2 | Very low suitability | 4 | Moderate suitability |
| 8.0–11.0 | 3 | Low suitability | 3 | Low suitability |
| 11.1–14.0 | 4 | Moderate suitability | 2 | Very low suitability |
| 14.0–20.0 | 5 | High suitability | 1 | Unsuitable |

Available water storage values are assigned based on the soil moisture range the map shows five levels of suitability scores for different ranges of soil moisture. Since the soil moisture is not homogenous within the watershed, runoff values will vary. The range of values starts from 1 up to 20. The suitability scores are unsuitable, very low suitability, low suitability, moderate suitability, and high suitability.

#### 4.1.3.2 Saturated Hydraulic Conductivity of Soil (Ksat)

Based on the Ksat analysis, 1 represents unsuitable areas, 2 is very low suitability, 3 represents low suitability and 4 moderate suitability (Table 6).

**Table 6: Assigned ksat scores for both runoff and run on areas for different ranges of values**

| | Runoff Areas† | | Run on Areas† | |
|---|---|---|---|---|
| **Range of Values** | **Scores** | **Interpretation** | **Scores** | **Interpretation** |
| 0-0.91 | 1 | Unsuitable | 4 | Moderately suitable |
| 0.91-3.0 | 1 | Unsuitable | 4 | Moderately suitable |
| 3.0-9.0 | 4 | Moderately suitable | 1 | Unsuitable |
| 9.0-28.0 | 3 | Low suitability | 4 | Moderate suitability |
| 28.0-141.0 | 2 | Very low suitability | 5 | High suitability |

The scores are assigned based on the range values. These values represent the infiltration rate of water towards soil horizons. According to the National Soil Survey Center Natural Resources Conservation Service, 6 classes are describing the infiltration range values. Suitability scores were assigned based on this range. The table shows very low, low, moderately low, moderately high, high, and very high classes. For suitability purposes, very low, low, high and very high Ksat values are considered unsuitable, very suitable, and low suitable for runoff values, respectively.

#### 4.1.3.3 Threshold Depth Value

Threshold depth runoff scores range from 1 to 5 based on scores (Table 7). This means 1 is unsuitable for runoff areas, whereas 2 is very low suitability, 3 represents low suitability, 4 moderate suitability, and 5 high suitability for runoff areas.

**Table 7: Assigned threshold depth scores for both runoff and run on areas for different ranges of values**

| | Runoff Areas† | | Run on Areas† | |
|---|---|---|---|---|
| **Range of Values** | **Scores** | **Interpretation** | **Scores** | **Interpretation** |
| 6.0-10.0 | 5 | High suitability | 1 | Unsuitable |
| 10.0-15.0 | 4 | Moderate suitability | 2 | Very low suitability |
| 15.0-30.0 | 3 | Low suitability | 3 | Low suitability |
| 30.0-53.0 | 2 | Very low suitability | 4 | Moderate suitability |
| 53.0-119.0 | 1 | Unsuitable | 5 | High suitability |

Threshold depth value ranges were assigned based on the curve number values. The threshold depth value ranged from 6 to 119. The map shows five different values with the suitability scores of runoff and run on.

### 4.2 Runoff Suitability Map

Based on the analysis using land use/land cover, surface structures, soil available water storage, soil saturated hydraulic conductivity, and threshold depth, a runoff suitability map was created (Figure 4). There are some parts of the upper side of the watershed that would be suitable for runoff. However, these regions are far from the run on areas, and it may not be convenient to collect water from these areas depending on the RHT being used. Based on the land use map, those areas are mostly shrub areas. The highly suitable areas were mostly located in the upper side of the watershed, even though the rock part of the watershed had some highly or moderately suitable areas. Since the land use and land cover is a shrub, this might be related to surface structure (concave, convex, and flat areas) which is mixed in the region. The other point is that those areas contain A, C, and D (mostly) hydrologic groups which had different values in terms of runoff capacity; while group A has a low runoff capacity group D has high runoff capacity. There was not a large variation in terms of ksat in the area. On this side of the watershed, there is not much variation in terms of available water storage as well. The AWS varied from 1.05 to 7.91 with 7.94 to 11 in some areas which are small in percentage.

Flow direction is another aspect of interpreting the runoff map. According to the flow direction map, water flows through from the upper side in which the slope is high to the flat or concave areas. This explains some highly or moderately suitable areas in terms of runoff. Within the watershed, water mostly comes from the north side of the watershed towards the southern side. The slope is another factor that needs to be considered in terms of collecting water for run on areas. The flat areas for which slopes are 0-6% are more suitable to capture water and some of these areas overlap with the crop areas. Since run on areas are identified around or close to crop areas, the methodology developed in this study is suitable for identifying run on areas in addition to runoff areas.

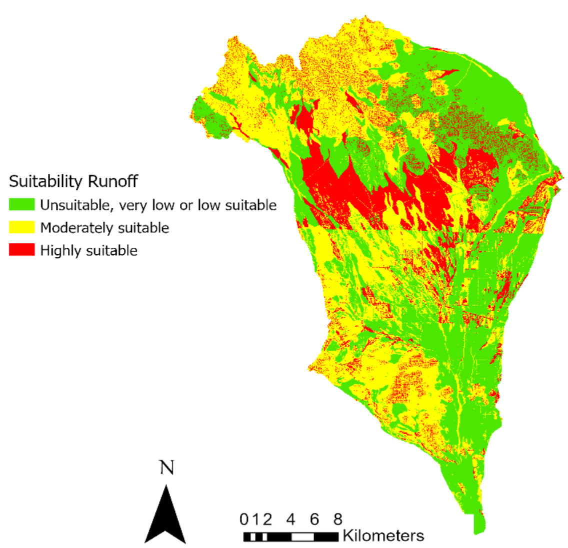


**Figure 4: Suitability map for runoff and run on areas for study watershed**

### 4.2. Runoff Availability

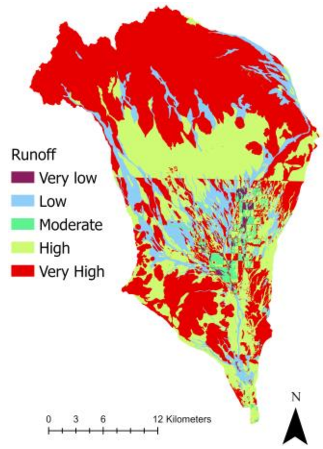


**Figure 5: Runoff volume map for different amount of runoff for study watershed**

# 5. DISCUSSION

Arid and semi-arid areas have a drought problem throughout the year, and this causes a problem during the plant growth period. To provide water that plants need in a growth period, available water needs to be captured in situ. For that purpose, surface runoff suitabililtiy needs to be determined. In this study, GIS and hydrological approaches were used to obtain run on and runoff areas. A ranking method was used to determine suitability areas within the study watershed. Results showed that this watershed mostly consisted of shrubs with grassland and crops. Areas chosen as suitable for run on were those in lower-lying areas on the southern end of the watershed. These coincided with current crop areas in the watershed, thus indicating the accuracy of the method and suitability maps. Available water storage was more on the areas for which the slope was much higher. The high slope areas were also found appropriate for runoff. The different slopes (Table 8) were used to recommend RHT for the different areas. Based on the table and slope map, different types of techniques are applicable for areas with up to 65 % slope.

To conduct a similar study, the researcher should be aware of certain parameters that are scored before the calculation/aggregation process. For example, similar land cover types such as developed open space, developed low medium, and high residential areas can be combined as developed areas. Similarly, fallow, idle cropland, and barren land can be categorized into one class. The soil parameters such as available water storage, Ksat, and soil hydrologic group play the most important role in this research. Soil hydrologic group is the most important factor in terms of calculating runoff volumes and relating with available water storage and Ksat. In this study, rainfall data used to create the runoff map was generated using the LARSWG software. Weather generators provide a good resource if a large part of weather data is missing.

For this study, ground-truthing will be a good idea to verify the areas for suitability analysis. Doing this will give researchers a better idea of the specific sites that are suitable for runoff and run on areas, as the data allowed researchers to be accurate in analysis and further site analysis.

## 5.1 Recommended Techniques for Insitu Rainwater Harvesting

There are water harvesting methods used for different purposes (Critchley and Siegert, 1991). Some techniques have similarities to each other. While some of the techniques might have different names in different areas, others might have similar names. Theoretically, however, these might be different techniques. For example, tied-ridging is also commonly known as boxed-ridges, furrow dikes, furrow damming, basin listing, basin tillage, and micro basin tillage (Jones and Stewart, 1990; Wiyo et al. 2000). Check dams are also known as gully plugs. Overall, there are mainly two types of water harvesting methods in use (FAO Editor 1986): macro catchment and micro catchment water harvesting techniques.

**Table 8: Water harvesting techniques for different slopes and crops**

| Technique | Preferred Slope | Type of Crops |
|---|---|---|
| Inter-row water harvesting | 0-5% | Field crops, vegetables, trees |
| Semi circular bunds | 1-5% | Trees, range, fodder, field crops |
| Vallerani water harvesting | 2-10% | Bushes and trees |
| Negarim | 1-5% | Trees and bush crops |
| Meskat | 2-15% | Trees and busch crops field crops |
| Contour buds | 1-25% | Trees and bush crops range, range, field crops, vegetables |
| Small pits (zay) | 0.5-5% | Field crops, range |
| Contour bench terraces | 15-65% | Trees and bush crops |

# 6. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

This study determined the suitability of watershed areas for in situ runoff harvesting. Several factors which have an importance to determine runoff and runon areas were evaluated to determine suitability. The curve number method was used to calculate runoff. The combined geospatial ranking and statistical approach provided an adequate representation of watershed suitability. The methodology is simple and widely applicable (for example curve number doesn’t require numerous parameters).

This study is a proxy for arid and semi arid areas, particularly those which do not have much data. According to the results of this research, 17,615 ha (25% of the watershed area) were classified as being suitable or highly suitable as runoff sources, while 14,092 ha (20% of the watershed area) were better suited as run on collection areas. Total collectible runoff was determined on an average annual basis.

Using spatial and statistical approaches presented in this study, new studies can be done in the future. Runoff was calculated based on a ranking approach in this research. Besides the methodology and approaches in this study, different models can be used to compare and create more robust results with the new outcomes to provide water harvesting locations to decision makers and farmers. In this study, socioeconomic factors of the study are not considered. The future work could take these factors into considerations to expand the research work.

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