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Assessing the Performance and Cost Effectiveness of Rainwater Harvesting for High Tunnel Production Across Climates in the Continental United States

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ASSESSING THE PERFORMANCE AND COST EFFECTIVENESS OF RAINWATER HARVESTING FOR HIGH TUNNEL PRODUCTION ACROSS CLIMATES IN THE CONTINENTAL UNITED STATES

BY

MUSTAFA AYDOGDU

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THESIS ACCEPTANCE PAGE

Mustafa Aydogdu

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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Finally, I would like to acknowledge all the sponsors, South Dakota State University who have helped me in everything; I would not have been able to finish this research without their help.

CONTENTS

ABBREVIATIONS

Arkansas	AR
California	CA
Colorado	CO
Crop evapotranspiration	ET_c
Crop coefficient	K_c
Crop coefficient end	$K_{c\ end}$
Crop coefficient initial	$K_{c\ ini}$
Crop coefficient mid-season	$K_{c\ mid}$
Crop development	L_{dev}
Georgia	GA
Illinois	IL
Irrigation replacement	IR
Kentucky	KY
Late season	L_{late}
Michigan	MI
Missouri	MO
Precipitation	P
Rainwater harvesting	RWH
Reference evapotranspiration	ET_o
Runoff reduction	RR
South Dakota	SD
Texas	TX
Vermont	VT
Washington	WA

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ABSTRACT

ASSESSING THE PERFORMANCE AND COST EFFECTIVENESS OF RAINWATER HARVESTING FOR HIGH TUNNEL PRODUCTION ACROSS CLIMATES IN THE CONTINENTAL UNITED STATES

MUSTAFA AYDOGDU

2024

Several factors such as global climate change, population growth, urban and agricultural expansion, rising water demand, unequal water distribution, hydro-political conditions, declining water quality, rainwater scarcity, and temperature-induced drought contribute to water resource degradation. Rainwater harvesting (RWH) emerges as a sustainable solution, involving the collection and storage of rainwater for agriculture, livestock, and domestic use. RWH reduces reliance on municipal water, mitigates climate change impacts, and decreases runoff. Conventional RWH systems in the US vary in effectiveness. Increasing storage and water use enhances RWH effectiveness, improving stormwater runoff and reducing potable water use. High tunnel production of vegetable crops has a strong potential for use of RWH for both reduction in potable water use for irrigation and reduction in stormwater runoff, generated by the high tunnel roof's impervious surface. A high tunnel is an unheated greenhouse. The roof provides the source of runoff to fill the RWH tank and irrigation water for vegetable production inside the high tunnel. While RWH would be complementary with high tunnel vegetable production, there has been little research into the potential performance for irrigation replacement, runoff reduction, and cost-effectiveness.

This study evaluated a high tunnel roof with an RWH system in 12 states for growing tomatoes, cucumbers, and beets, focusing on irrigation, runoff reduction, and cost

analysis. Irrigation replacement, varying by state and tank size, shows that in CA, RWH can meet about 3% and 17% of irrigation needs for 250-gallon and 3000-gallon tanks, respectively, while in VT, it can reach 39% and 99%, respectively, with the highest IR (%). The optimal size for irrigation replacement is generally 1,500 gallons.

Rainwater harvesting effectiveness depends on tank size, rainfall, and crop types. States with lower rainfall during the growing season have higher percentages of runoff reduction. Rainwater harvesting for tomatoes is more cost-effective than for cucumbers and beets due to higher water use and a longer growing season. Runoff reduction is limited in most states, with CO having the highest flow reduction of 80%.

The economic benefits of rainwater harvesting depend on factors like local water prices, rainfall, and harvested rainwater amount. The most cost-effective scenarios include VT with the highest gain ($307) for a 1000-gallon tank, followed by KY ($1500) for a 260-gallon tank, and GA ($144) for a 1000-gallon tank. RWH is most cost-effective in regions with high rainfall during the growing season and expensive main water. While RWH may not be exceptionally economically advantageous for all regions, it can still provide benefits of runoff reduction, promoting cost savings and efficient use of potable water resources.

CHAPTER 1 : INTRODUCTION

1.1Introduction

Climate factors, particularly precipitation and temperature, directly and indirectly, influence agricultural sectors and other productive industries(Velasco-Muñoz et al., 2019a). Various factors contribute to the significant degradation of water resources, including the impacts of global climate change, swift population expansion, alterations in land use, the expansion of agricultural and urban areas, growing demands for water across various sectors, uneven distribution of water resources, regional hydro political circumstances, declining water quality due to excessive exploitation, scarcity of rainwater, and heightened evaporation rates and aridity resulting from rising temperatures (Fiaz et al., 2018; Liu et al., 2018)

Rainwater harvesting (RWH) is a sustainable and eco-friendly tool to adapt to water scarcity. It involves collecting and storing rainwater from rooftops, land surfaces, and other surfaces for future use. RWH has been practiced for centuries in many parts of the world, especially in arid and semi-arid regions where water is scarce. The investigation of the operational effectiveness of rainwater harvesting (RWH) systems has been a focus of study in various nations, such as Malaysia, Gaza, and Spain (Thesis et al., 2016). The collected rainwater can be used for various purposes such as irrigation, livestock, and domestic use. RWH can help reduce the demand for municipal water supply, which is often limited and expensive. It can also help mitigate the effects of climate change on water resources by reducing runoff and recharging groundwater. RWH can be done through a variety of methods such as recharge wells, check dams, percolation tanks, and injection wells that help direct rainwater into the ground to replenish aquifers(Hussain et al., 2019).

Traditional rainwater collection systems are commonly employed in urbanized regions across the United States to conserve water. However, they often experience overflow during rainfall and offer limited effectiveness in reducing runoff (Roman et al., 2017). To improve runoff reduction performance, RWH system storage can be increased and the utilization of stored water the utilization of RWH systems and increase usage, thereby increasing the available storage between rain events.

1.2 Objectives

The overall goal of this study is to assess the viability of Rainwater Harvesting (RWH) for high tunnel production across a range of climate conditions in the continental United States. RWH feasibility was assessed for three variables: tank size (seven tank sizes from 25 gallons to 3,000 gallons), climate (30 years of precipitation and evapotranspiration data from 12 locations across the continental US), and crop type (tomatoes, cucumbers, and beets). The assessment was performed using a daily water balance model that tracked runoff generated from rainfall, volume into the tank, volume out of the tank via ET (crop water demand), volume of overflow if the tank were full. Specific objectives were:

1. Assess runoff reduction performance of RWH for high tunnel production.
2. Assess irrigation replacement performance of RWH for high tunnel production.
3. Assess cost-effectiveness of RWH for high tunnel production.

1.3 Outline of the Thesis

This study consists of 4 chapters. Chapter 1 provides a general overview of the importance and applications of Rainwater Harvesting (RWH). Additionally, it outlines the objectives of this study. Chapter 2 presents a general perspective on previous studies related to RWH, focusing on the selected study areas with an emphasis on runoff reduction, irrigation, and cost-effectiveness. Chapter 3 details the materials and methodology of the RWH system followed in the study, as well as the results and discussion. Chapter 4 discusses a summary of conclusions and future work.

CHAPTER 2 : Literature Review

2.1 Literature Review

Rainwater harvesting (RWH) is gaining increasing attention as a sustainable water management strategy, particularly in reducing runoff and mitigating the impacts of urbanization on natural hydrological processes (Huang et al., 2021). This literature review synthesizes findings from key studies on these systems, focusing on the effectiveness of rainwater harvesting systems in reducing runoff, irrigation replacement, and cost-effectiveness. The selected references provide valuable insights into various aspects of RWH, such as system design, implementation, and performance.

Rainwater harvesting, an ancient technique that is still used today to address flood and drought risks, has evolved with advanced technology at various levels (Raimondi et al., 2023). Studies have been carried out to assess the current state of rainwater harvesting, including rainwater treatment and management, and to assess its environmental and social advantages and link them to the “Sustainable Development Goals” (Thapa et al., 2022).

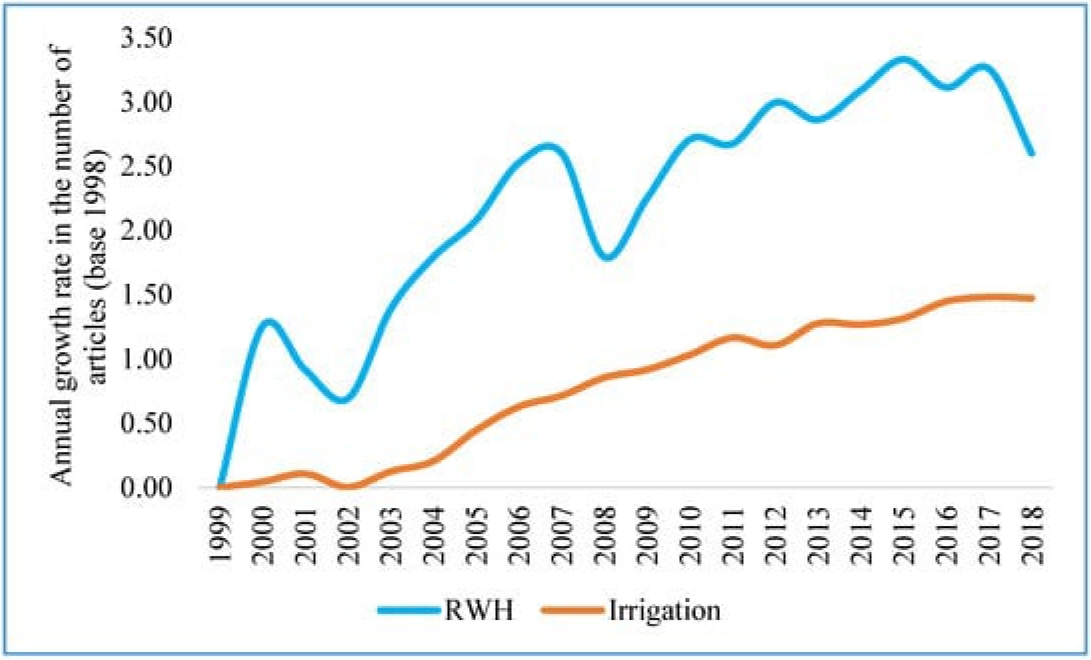

Figure (1) Comprises a selection of studies concerning rainwater harvesting for agricultural irrigation, and these studies were published from 1999 to 2018. This figure is from "Rainwater Harvesting for Agricultural Irrigation: An Analysis of Global Research" (Velasco-Muñoz et al., 2019b).

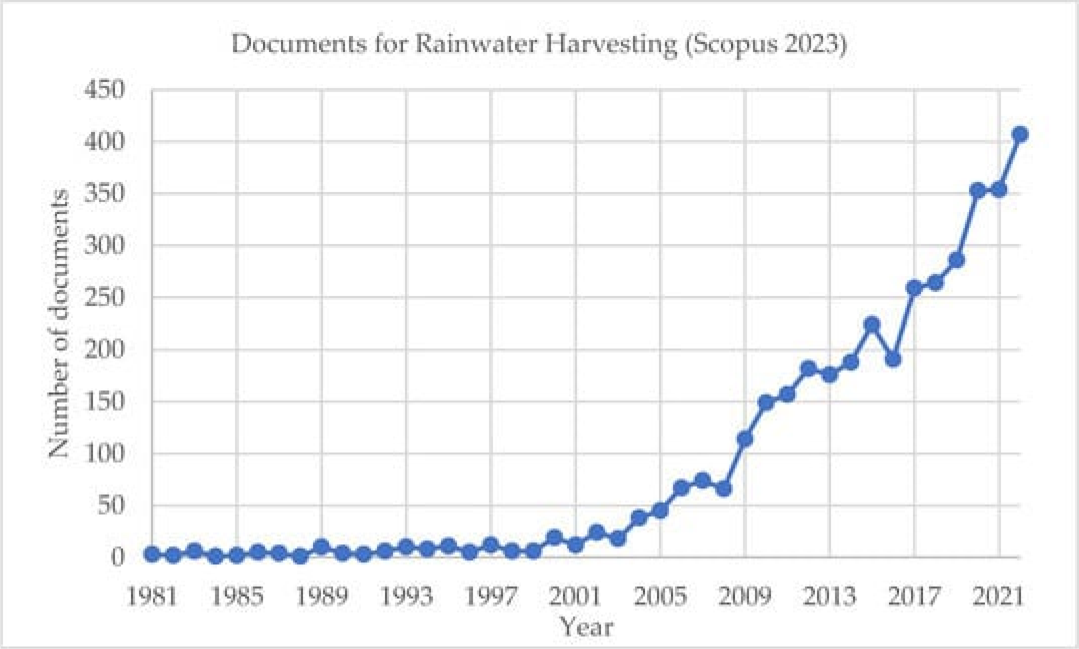

Figure (2) Quantity of records in Scopus (as of February 6, 2023) associated with the term "rainwater harvesting. This figure is from " Rainwater Harvesting and Treatment: State of the Art and Perspectives (Raimondi et al., 2023b).

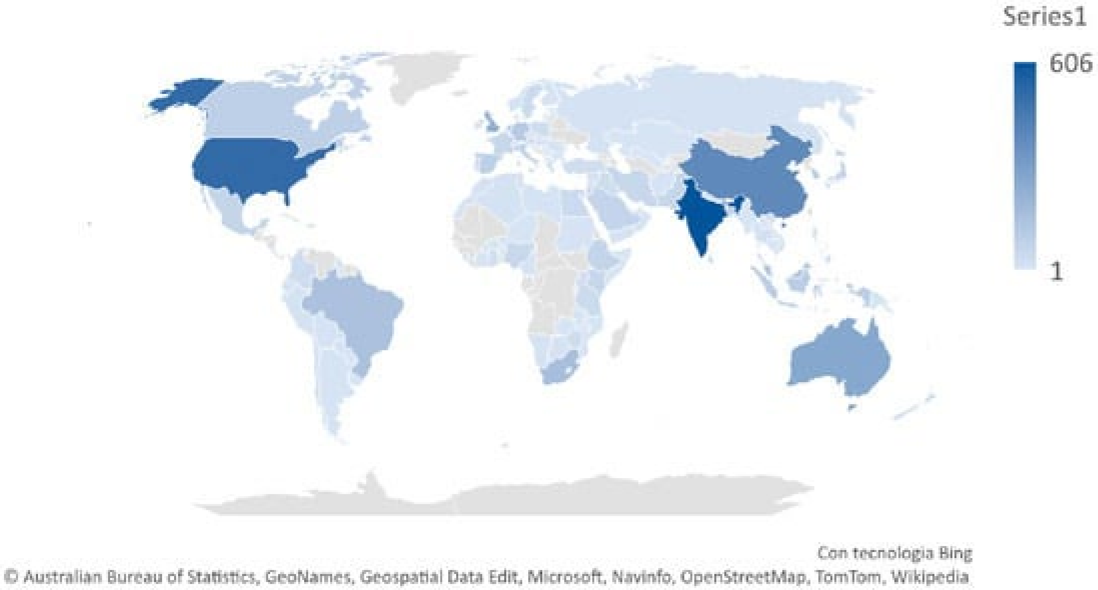

Figure (3) Global dispersion of papers related to the keyword "rainwater harvesting" (Scopus search as of February 6, 2023). This figure is from " Rainwater Harvesting and Treatment: State of the Art and Perspectives (Raimondi et al., 2023b).

Indexed by Scopus the number of articles and studies published on RWH has increased dramatically between 2016 and 2022 (Figure 2) (Raimondi et al., 2023b). However, there are few studies on the use of RWH for irrigation in agriculture and for high tunnel production. This study is intended to contribute to this gap. Generally, most research has examined the use of water from RWH for domestic needs or stormwater management. Although urbanization and climate change make the use of RWH for residential areas beneficial, its use in agriculture has great potential.

2.2 Runoff Reduction

The expansion of urban areas, climate fluctuations, and the contracting spaces of cities (reduction of water-permeable areas in cities such as parks, garden, etc.) have placed significant pressure on centralized water management infrastructure. Impervious cover dramatically alters the hydrology of urban landscapes, generating significantly higher runoff volume and peak flows, this has resulted in water scarcity and urban flooding in numerous cities (Yildirim et al., 2022). Projections indicate that by 2050, urban water demand may surge by an additional 80% due to population growth and increased affluence (Flörke et al., 2018). Various technologies have been deployed to address these challenges, and among decentralized solutions, rainwater harvesting (RWH) has garnered considerable interest from researchers aiming to combat water scarcity and urban flooding in cities(Semaan et al., 2020).

While many previous reviews of rainwater harvesting systems have focused on the water-saving features, limited research has examined the impact of these systems on rainfall-runoff reduction. In research Kim et al., 2012 who used a rainfall-runoff reduction model based on analytical probability analysis. This research involved computing rainfall-runoff reduction using the water balance equation, cumulative distribution, and probability density, as well as mean functions for rainfall-runoff. However, the paper does not address potential limitations or assumptions made in the analytical probabilistic model used for estimating rainfall-runoff reductions. Another method involves evaluating the effects of rainwater harvesting on stormwater runoff reduction using hydrological models like HEC-HMS, but this research has been limited to residential (Custódio & Ghisi, 2023). Additionally, this report does not discuss the long-term impacts or sustainability of rainwater harvesting.

The Rainwater Analysis and Simulation Program (RASP) model was developed to simulate the functionality of rainwater harvesting (RWH) systems in terms of water supply and the reduction of runoff (Cahyono, 2022). Several other studies have investigated various aspects of RWH on runoff reduction, including spatial design, optimization models, and real-time control methods. For example, a system was employed as a rain simulation model to assess decentralized RWH systems aimed at providing water supply and reducing runoff in diverse land use scenarios throughout the state of Virginia, USA (Sample & Liu, 2014; Sepehri et al., 2018).

The reduction of runoff through RWH technology may vary depending on the specific parameters of the technique. In the tank storage system employed in our study, runoff reduction is not solely dependent on tank size; it is also directly related to the utilization of the water in the tank. Additionally, once the amount of water stored in the tank reaches its capacity, there is no further runoff reduction. Our study found that key elements for enhancing the reduction of potable water use, achieving financial savings, and realizing environmental benefits in rainwater harvesting systems include maximizing and diversifying water applications, optimizing system design, integrating rainwater harvesting into a comprehensive sustainable water management plan, and evaluating its feasibility against practical site options rather than idealized alternatives.

Previous research indicates that RWH systems used in buildings have the potential to achieve potable water savings ranging from 20 to 65%. Additionally, the literature suggests that these systems could lead to a reduction in runoff volume by 13 to 91% (Teston et al., 2022). In a study by Sepehri et al., 2018,it was demonstrated that RWH has the potential to decrease runoff volume by 3% to 47% in an urban basin located in the center of Illinois, USA. A study using the SWMM model in the Chollas Creek watershed in San Diego, California, showed that volumetric reductions increase linearly with capacity and application, with maximum reductions ranging from 10.1% to 12.4% for different RWH storage sizes (Walsh et al., 2014). A study discovered that in the residential area of Nanjing, China, Rainwater Harvesting (RWH) tanks exhibit effective performance in alleviating urban waterlogging issues. They observed reductions of 13.9%, 30.2%, and 57.7% in flood volumes for maximum daily rainfall, annual average maximum daily rainfall, and critical rainfall, respectively (Zhang et al., 2012).

Another study analyzed the effectiveness of residential rainwater harvesting systems in 23 US cities in contributing to water supply and stormwater runoff reduction. A decrease in non-potable water demand ranging from 30% to 50% was accomplished using compact (190 L) storage barrels, with the reduction being more significant in the dry Western regions and comparatively larger in the Middle East. Additionally, there was a reduction of about 20% in runoff in the arid West and lesser decreases in more humid areas. These findings reveal that rainwater harvesting has shown remarkable efficiency in saving water for non-potable indoor use in certain regions. Furthermore, rainwater harvesting serves as a valuable stormwater management measure by reducing runoff volume and providing an alternative water source for both US cities and their residents (Steffen et al., 2013).

Another research highlights the components of a typical RWH system, including the roof pond, filter, storage tank and pump, and discussing potential water quality benefits through runoff reduction (Sample & Liu, 2014). However, this paper does not address the potential land-use scenarios.

The findings imply that certain rainwater harvesting (RWH) systems tailored for present conditions might experience diminished efficacy in the future owing to climate change in specific locations across the United States. The results highlight a projected decline in the efficiency of rainwater harvesting systems for capturing runoff in the eastern, northwestern, and southeastern US. Conversely, in the western, southern, and central US, these systems are anticipated to become less effective in fulfilling water supply needs in the future(Alamdari et al., 2017).

2.3 Irrigation Replacement

Meeting the demand for food poses a significant challenge for humanity in the 21st century (Hasan et al., 2018). Agricultural ecosystems, serving as the primary food source, also stand as the predominant consumers of global water resources concurrently (Damkjaer & Taylor, 2017; Forouzani & Karami, 2011). The utilization of available water by these ecosystems ranges between 60% and 90%, depending on the region's climate and economic development (Adeyemi et al., 2017; Velasco-Muñoz et al., 2018). The worldwide extent allocated to irrigated crops is estimated at 275 million hectares, with an annual increase of 1.3% (Velasco-Muñoz et al., 2019a).

Rainwater harvesting emerges as a promising alternative to traditional irrigation methods, especially in areas with limited water resources (Velasco-Muñoz et al., 2019a). While rainwater storage is commonly employed for outdoor irrigation or indoor activities such as flushing toilets, doing laundry, and cleaning rooms, the integration of readily available water treatment solutions allows a rainwater harvesting (RWH) system to extend its utility beyond drinking purposes, fulfilling various domestic needs (Cahyono, 2022).

Previous studies have predominantly focused on the outdoor and indoor use of rainwater from the roof of a building rather than on irrigation with RWH systems in agriculture. However, leading efforts in India, China, the United States of America (USA), South Africa, and the Netherlands aim to utilize RWH for irrigation in agriculture. An analysis of global research on rainwater harvesting for agricultural irrigation over the last two decades found that it has been studied by different disciplines in recent years (Velasco-

Muñoz et al., 2019b). While there has been a significant increase in research related to RWH, there has been very little research exploring the feasibility of RWH for high tunnel applications.

The practice of RWH contributes to retaining water, fulfilling a portion of irrigation requirements, and, through storage, alleviating shortages during droughts and dry seasons. Diverse applications of this irrigation method have resulted in enhanced crop yields and improved water utilization efficiency in various global regions, helping to alleviate the adverse effects of climate change on agriculture (Velasco-Muñoz et al., 2019b). As an illustration, Australians commonly gather rainwater in subterranean reservoirs as a response to water scarcity in rural regions. In multi-unit residential complexes in Australia, up to half of the required water for activities like toilet flushing, laundry, hot water, and outdoor irrigation can be sourced from the practice of rainwater harvesting (Traboulsi & Traboulsi, 2017).

B. R. Sharma, n.d.; Jin, 2016 assessed the effectiveness of regional rainwater utilization and the increased crop yield resulting from additional irrigation across various crops. Their findings indicated that “water harvesting, and supplementary irrigation demonstrate economic viability at the national scale.” The net benefits showed a threefold improvement for rice, fourfold for pulses, and sixfold for oilseeds. The study also highlighted that farmer equipped with supplementary irrigation experience minimal productivity impacts during droughts.

In the literature review, there are few specific studies on irrigation replacement in agriculture. However, the present study attempts to contribute to filling this gap. As evidenced by a range of performances across climate conditions and tank sizes, research across a range of climate conditions is needed.

2.4 Cost Effectiveness

Studies on this topic have predominantly focused on the cost analysis of the Rainwater Harvesting (RWH) technique for domestic use, with limited exploration of its cost-effectiveness. Our study aims to fill this gap, particularly by conducting a cost-effectiveness analysis using current tap water prices, a less-explored aspect in the existing literature. Like previous studies using the cost of municipal water, our study uses the same methodology. Our focus is on real-time cost-effectiveness. This involves considering both system costs and the amount of stored water used for irrigation, and focusing on the period when crops are grown to identify potential savings.

The study titled "Harvesting System and Conventional Sources of Water," published in the journal Water Resources Management by Abdul Salam Khan, 2023 compares the performance and cost-effectiveness of rainwater harvesting systems with conventional water sources. The findings suggest that a rainwater harvesting system is more cost-effective than conventional water sources but requires integration with a government supply line to meet the demand for non-potable water. The research also delves into the challenges and adequacy of existing water sources for both potable and non-potable demand.

In another study conducted in the Chollas Creek watershed in San Diego, California, previously mentioned in the Runoff Reduction section, a cost-effectiveness analysis revealed that the 227-L rain barrel provided the greatest cost-effectiveness. This barrel reduced an average of 6500 L of runoff per dollar invested during the analysis period

(Walsh et al., 2014). This study aims to assess the stormwater management benefits of a storage-based Rainwater Harvesting (RWH) scheme in a densely urbanized, semi-arid region. It particularly emphasizes the smaller RWH configuration of 227-liter rain barrels, identified as the most cost-effective option. The research highlights the need for targeted hydrological measurements, cost-effectiveness analysis, and comparisons with other stormwater management practices to identify the most appropriate option for implementation at the catchment scale.

CHAPTER 3: RWH Modeling

3.1 Introduction

Rainwater harvesting (RWH) encompasses various methods for collecting and storing rainwater for future use. The most common RWH methods include surface runoff harvesting and rooftop rainwater harvesting. In this study, a rooftop rainwater harvesting technique was simulated as a 60ft x 40ft high tunnel roof. The methods and calculations applied in this study can be summarized in a schematic diagram from a general point of view. (Figure 4). Detailed calculations are provided in the Materials and Methods section.

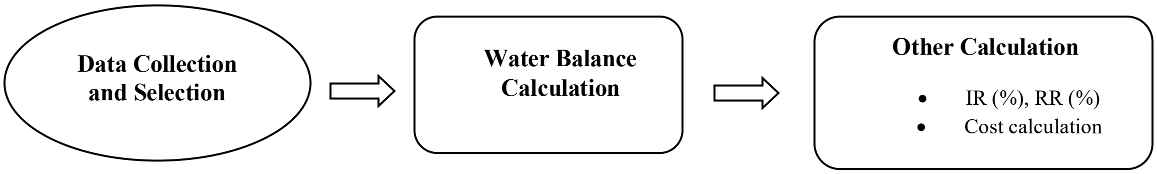

Figure (4) Summarizes the methods and calculations applied in this study.

3.2 Materials and Methods

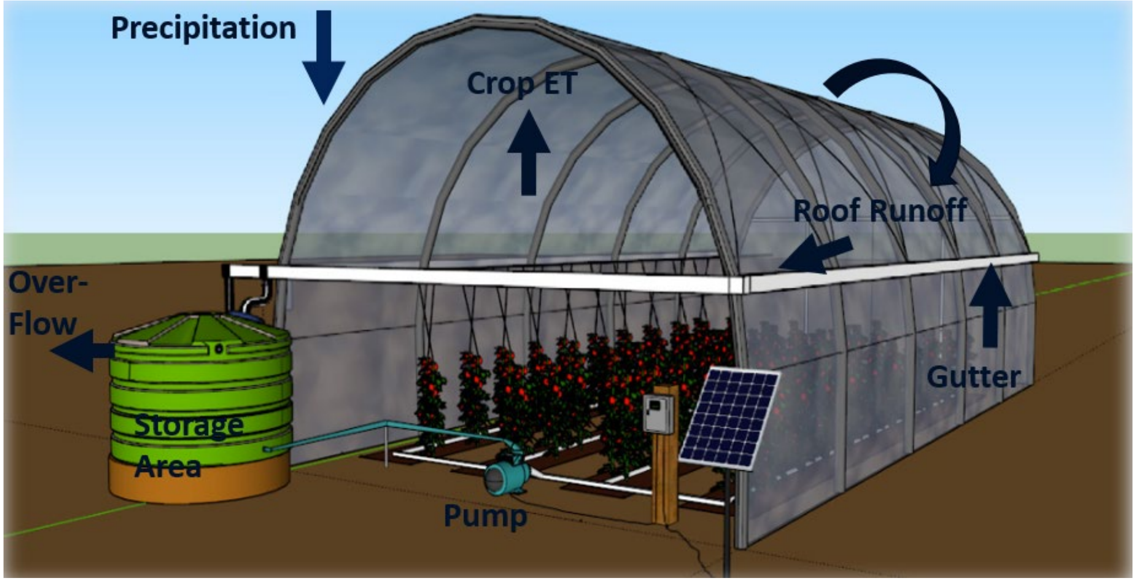

Figure (5) High Tunnel Rainwater harvesting system. Storage area varies from 250 gal to 3000 gal. RWH Demonstration for high tunnels. (DOI: 10.1016/J.PROENG.2015.06.105)

This study investigated the effect of location (climate), crop type, and tank size on the performance of rainwater harvesting for high tunnel production for runoff reduction, irrigation replacement, and cost effectiveness. Three crops were selected that represented high, medium, and low water use crops that would be produced in high tunnel vegetable production (tomato, cucumber, and beets). The effect of tank size was evaluated across 7 different tank sizes, ranging from 250 gallons (946 L) to 3,000 gallons (11,356 L) (250 gals (946 L), 500 gals (1,892 L), 1000 gals (3,785 L), 1500 gals (5,678 L), 2000 gal (7,570 L), 2500 gals (9,463 L), and 3000 gals (11,356). Cost-effectiveness was also estimated by assuming a flat cost of $1 per gallon of tank size and using water rates specific to each municipality.

States	Counties	Av. Annual Precipitation (inches)	Av. Annual Precipitation (mm)	Av. Eto (Reference ET) (inches)	Av. Et$_o$ (Reference ET) (mm)
AR	Conway	52	1323	51	1305
CA	Madera	25	639	57	1464
CO	Pueblo	13	353	39	1006
GA	Bleckley	48	1226	56	1440
IL	Peoria	38	973	43	1107
KY	Adair	54	1372	45	1161
MI	Clare	33	859	36	922
MO	Benton	43	1108	50	1270
SD	Stanley	19	489	46	1171
TX	Hamilton	32	836	66	1687
VT	Washington	46	1183	32	820
WA	Lewis	68	1731	34	883

Table (1) Counties of the states, average annual precipitation, average annual reference ET.

Figure (6) This is a map of the Continental United States. The red arrows indicate states that were selected to assess the performance of rainwater harvesting for high tunnel production. It does not represent the selected counties. Map source is Google Maps (https://www.google.com/maps).

The high tunnel size was set at 40 x 60 feet (12.2 x 18.3 m) for a total area of 2,400 ft^2 (222.9 m^2) and was consistent across all locations. Within the high tunnel, a cultivation area representing 80% of the available space was designated for the selected plants (178.4 m^2).

In some cases, a double crop was possible if the crop had a short time to maturity and the growing season was long. In those cases, it was assumed that there would be one week between each growing season to enable adequate preparation time between crops.

3.2.1 Plant selection

Water use varies by crop type and impacts the feasibility of rainwater harvesting for high tunnel production. Three crop types (tomatoes, cucumber, and beet) were evaluated to assess the impact of a high, medium, and low water use plant that would be grown in a high tunnel application.

The crop coefficient (K_c) is a scaling variable that is used to scale evapotranspiration (ET) as compared to a reference crop. There are two reference crops- grass (short crop) and alfalfa (tall crop), usually a grass at a uniform prescribed from chapter 5 (Allen & Pereira, 2006). In this study grass (short crop) used for reference ET.

The selected plant K_c values were obtained from the Food and Agriculture Organization (FAO) website's Chapter 6 section (Allen & Pereira, 2006).The K_c values are characterized by specific values that are contingent upon the plant species and vary depending on the plant's developmental stage.

To determine the daily water requirements of the planted crops, K_c values were calculated by dividing the plant growth stages into four distinct parts: the initial stage ($K_{c\ ini}$) from the previous mentioned chapters crop development stage, mid-season stage ($K_{c\ mid}$), late-season stage, and end-season stage ($K_{c\ end}$). These K_c values were then used to estimate the amount of water required for the growth and development of the selected plant species (Equations 1 and 2). K_c values represent a set of standardized coefficients for various plant species suitable for cultivation in a high tunnel environment, categorized into four different stages of the growth process. Plant selection was made to account for a wide range of K_c values. This range in water use provides insight into irrigation management strategies for many other plant species.

The development stage K_c value was determined by interpolating between the $K_{c\ ini}$ and $K_{c\ mid}$ values and is dependent on the plant's development time. Similarly, the late-stage K_c value is calculated by interpolating between the $K_{c\ mid}$ and $K_{c\ end}$ values (Figure 8, Table 2). The following equations were used to calculate interpolation (Equations 1 and 2).

$$K_c \text{ Development} = \frac{Kc\ mid - Kc\ ini}{L_{dev}} \text{.................}1$$

$$K_c \text{ Late} = \frac{Kc\ mid - Kc\ end}{L_{late}} \text{....................................}2$$

Here L_{dev} and L_{late} values are taken from table two for development day and late day.

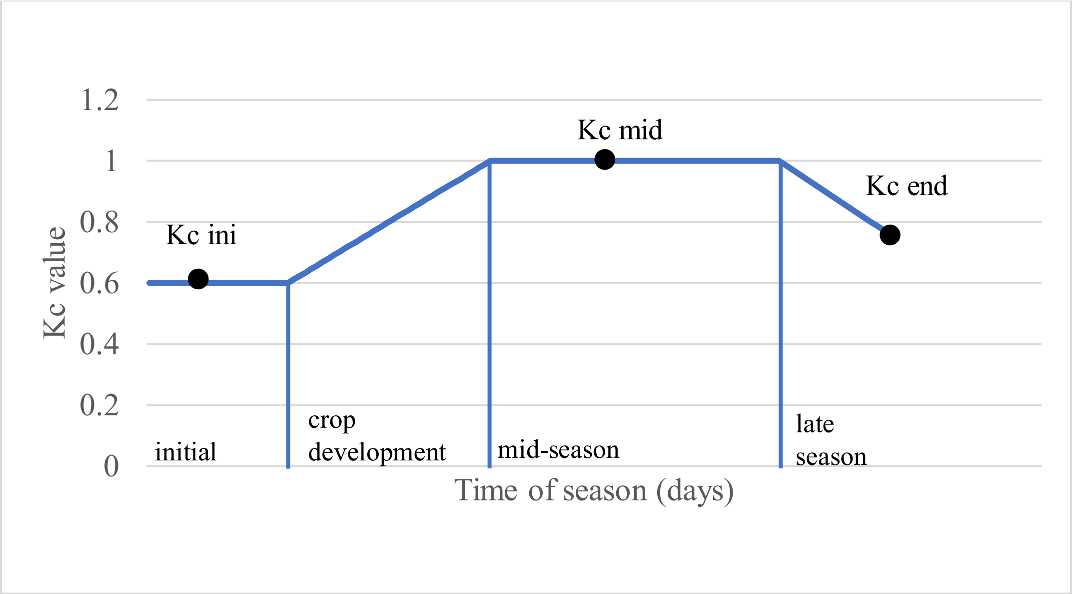

Figure (7) Crop coefficient values stages. Kc value on the y-axis, plant growing time on the x-axis. Kc values for cucumber. Kc value (0-1.4) on the y-axis, and tomatoes, cucumber and beet plants growing time (155 days), (130 days), and (70days) on the x-axis respectively.

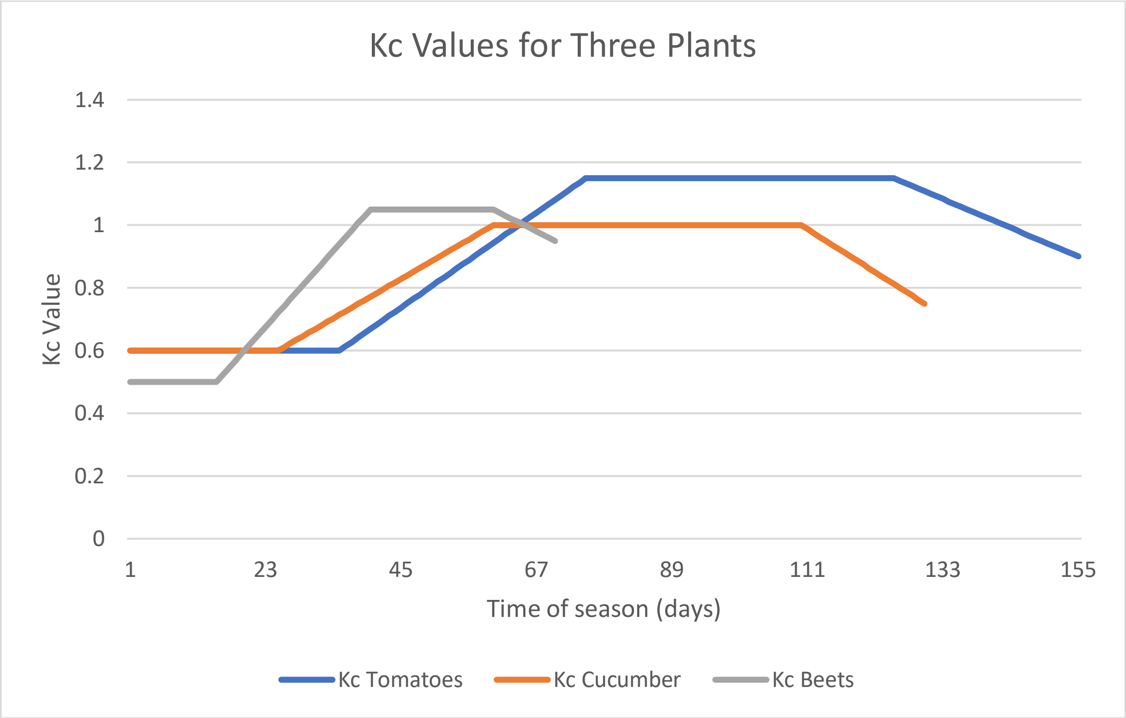

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Figure 8 Crop coefficient values Kc values for tomatoes, cucumber, and beets. For tomatoes K_c value (0-1.4) on the y-axis, tomatoes plant growing time (155 days) on the x-axis. Initial; 35 days, crop development; 40 days, mid-season; 50 days, and late season; 30 days. For cucumber Kc value (0-1.4) on the y-axis, and cucumber plant growing time (130 days) on the x-axis. Initial; 25 days, crop development; 35 days, mid-season; 50 days, and late season; 20 days. For beet Kc value (0-1.4) on the y-axis, and beet plant growing time (70 days) on the x-axis. Initial; 15 days, crop development; 25 days, mid-season; 20 days, and late season; 10 days.

Plant	Growth Cycle (Days)	L_{ini} (days)	L_{dev} (Days)	L_{mid} (Days)	L_{late} (Days)	Kc ini	Kc mid	Kc end
Tomatoes	155	35	40	50	30	0.6	1.15	0.9
Cucumbers	130	25	35	50	20	0.6	1	0.75
Beets	70	15	25	20	10	0.5	1.05	0.95

Table 2 Three plants' growing periods and Kc values. Here, the Kc end value for the tomato plants is between 0.7-0.9, and a value of 0.9 is taken for water balance calculation.

The lengths of growth periods for tomato, cucumber, and beet plants were obtained from Table 11 in Chapter 6 of fao.org (Allen & Pereira, 2006). These periods were subsequently divided into four distinct phases, including the initial, dev, mid, and late stages, for each plant species under consideration.

The length of the development stage of tomatoes covers 40 days from planting to mid-stage. During this period, $K_{c\ dev}$ values increased from 0.6 to 1.15. For $K_{c\ late}$, K_c decreased from 1.15 to 0.9 within a time frame of 30 days (Figure 8). The high $K_{c\ end}$ value of 0.9 for tomato is included in the relevant calculations. In this context, the product development stage values given in fao.org Chapter 6 Table 11 are used to facilitate the daily calculation of both product development and late season K_c values (Allen & Pereira, 2006).

For cucumber, these values increased from 0.6 to 1 during the development period, which took 35 days for $K_{c\ dev}$. For $K_{c\ late}$, it was calculated For $K_{c\ late}$, it was calculated that it decreased from 0.9 to 0.75 in 20 days. (Figure 8).

For the last selected plant, the beet, a daily increase in the developmental stage Kc value between 0.5 and 1.05 was determined. For $K_{c\ late}$, it was calculated that it decreased from 1.05 to 0.95 in 10 days (Figure 8).

3.2.2 Tank sizing

The use of seven different tank types, ranging from 250 gallons to 3000 gallons, in this study is based on a few key reasons. The primary objective was to determine the optimal tank size for each geographic region, considering their current availability and changing climatic conditions to avoid unnecessary costs. The smallest tank size is 250 gallons and the selected tank sizes were examined from 500-gallon tank size up to 3000-gallon tank in 500-gallon increments. These tank sizes were chosen because they were considered to be feasible sizes for use and represented an upper and lower limit of what a grower might use for their operation. It was also estimated that 500-gallon increments in tank size could provide a narrow enough increment to determine the break point for each assessment (runoff reduction, irrigation replacement, and cost effectiveness). In addition, tanks are not typically available in odd sizes, so if a break point was determined to be a size that was not available, then the information would be an academic exercise rather than a useful application.

The assessment focuses on three key areas to evaluate the effectiveness of tank sizes. First, it examines the extent to which rainwater collected in these tanks can meet the daily water needs of crops grown in high tunnels. Second, it explores the effectiveness of these tanks in mitigating runoff triggered by precipitation events. Third, it evaluates the cost effectiveness of each tank size for each location.

Valuable insights can be gained using these methods in the investigation. Not only is the calculation of installation costs associated with adopting rainwater harvesting techniques in high tunnels improved, but it also assists in selecting tank sizes that show the most optimal efficiency based on geographic location. This information can assist in making informed decisions regarding rainwater harvesting practices in high tunnels. Figure 5 shows a representative application of rainwater harvesting in high tunnels.

3.2.3 Growing season

The growth periods of the three selected crops are shown in Table 4 from the same mentioned book previously (Chapter 6)(Allen & Pereira, 2006). Considering the 31-year meteorological history of the 12 selected provinces of the states, date ranges without frost events were selected. The findings revealed that the growth periods of the selected plant species differ across the continental US. In order to determine these periods correctly, certain time intervals were selected depending on the absence of frost events. To determine these intervals, frost data was obtained from a web resource that compiles data from the National Weather Service and is frequently used by home gardeners (Davesgarden.Com, n.d.). All frost window applications used, source their data from the National Weather Service.

In states with a short growing season, the growing season of the selected plants was determined by extending the growing intervals by up to fifteen days, provided that there was no hard frost and that the growing intervals were almost certain to be frost-free.

The closed environment provided by the high tunnels will likely reduce the impact of external weather conditions (Nikolaou et al., 2020). In this way, it has provided flexibility in optimizing the growing periods according to the counties, except for the time intervals when there is a certain risk of frost.

States	Average risk of freezing, on (dates)	Almost certain risk of freezing, on (dates)	Almost certain no risk of freezing, (dates)	Frost-free growing season (days)	Growing range for Tomatoes (dates)	Growing range for Cucumber (dates)	Growing range for Beets (dates)
AR, Conway	10/31 - 4/1	11/14 – 3/17	4/16 – 10/16	213	4/16 – 9/17	4/16 – 8/23	4/16 – 6/24 7/12 – 9/9
CA, Madera	11/15 - 3/5	12/4 – 1/28	4/10 – 10/29	255	4/10 – 9/11	4/10 – 8/17	4/10 – 6/18 6/26 – 9/3
CO, Pueblo	10/20 - 4/30	9/20 -5/14	5/14 – 9/20	158	5/1 – 10/2	5/1 – 9/7	5/1 – 7/9 7/17 – 9/24
GA, Blakely	11/9 - 3/9	12/2 -2/18	3/28 – 10/20	245	3/28 – 8/29	3/28 – 8/14	3/28 – 6/5 6/13 – 8/21
IL, Peoria	10/7 - 4/28	10/23 – 4/13	5/14 – 9//21	162	5/1 – 10/6	5/1 – 9/7	5/1 – 7/9 7/17 – 9/24
KY, Adair	10/20 - 4/18	11/2 – 4/3	5/2 – 10/6	185	5/2 – 10/3	5/2 – 9/8	5/2 – 7/10 7/18 – 9/25
MI, Clare	9/24 - 5/16	10/8 – 5/3	5/30 – 9/11	131	5/4 – 10/5	5/4 – 9/10	5/4 – 7/12 7/20 – 9/27
MO, Benton	10/15 - 4/9	10/31 – 3/26	4/23 – 9/30	189	4/23 – 9/24	4/23 – 8/30	4/23 – 7/1 7/9 – 9/16
SD, Stanley	10/1 - 4/30	10/12 – 4/14	5/15 – 9/20	154	5/1 – 10/2	5/1 – 9/7	5/1 – 7/9 7/17 – 9/24
TX, Hamilton	11/9 - 3/25	11/24 – 3/5	4/15 – 10/26	229	4/15 – 9/16	4/15 – 8/22	4/15 – 6/23 7/1 – 9/8
VT, Washington	10/1 - 5/11	10/20 – 4/26	5/26 – 9/13	143	5/5 – 10/6	5/5 – 9/11	5/5 – 7/13 7/21 – 9/28
WA, Lewis	10/6 - 5/5	10/24 – 4/17	5/23 – 9/19	154	5/8 – 10/9	5/8 – 9/14	5/8 – 7/16 7/24 – 10/1

Table (3) Growing times of the three crops by state. Date ranges for the occurrence of frost events, date ranges for the occurrence of certain frost events and approximate growing date ranges for each region based on the number of days without frost events. Since beet has a short growing period, it is assumed that it is grown twice a year in each region and therefore two different date ranges are given for this crop. These data are current and may vary over time.

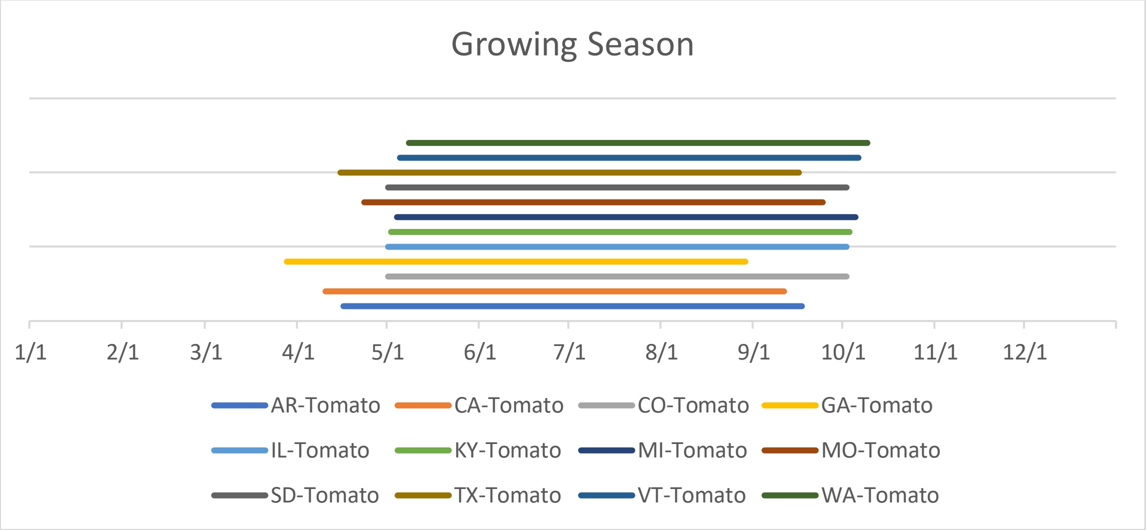

Figure (9) Growing season for tomatoes. It is taken for reference growing season and varies from state to state.

Since tomatoes have the longest growing period of the three selected plants, the growth period time intervals in the regions for the other two plants were adjusted according to the tomato plant. The date range selected for the growing season in Pueblo, Colorado covers the period from 20/9 to 5/14, when frost events are most likely to occur (Table 3). Given that the selected plants were tomato plants, which have the longest growing period of 155 days, it was imperative to select a date range that covered the frost period (5/1 - 10/2). It is assumed that the selected crops can be successfully grown in this date range, taking advantage of the protective environment provided by the high tunnel.

For Illinois, Michigan, South Dakota, Vermont, Colorado and Washington, a time frame for growing season has been established, with the exception of date ranges with almost certain risk of freezing. For these states, however, the range of almost certain no risk of freezing dates is slightly exceeded. For the remaining states of Arkansas, California, Kentucky, Missouri, Kentucky, Missouri, and Texas, the planting date ranges selected were almost certain no risk of freezing date ranges. As can be seen in Table 3, there are two different date ranges for beet. The reason for this is that it is designed to be grown twice a year because it has a shorter growing period than the other two crops.

3.2.4 Historic weather data

For this study, daily rainfall data and reference evapotranspiration (ET_o) from 1991 to 2022 were obtained for cities located in selected states. Thirty years of rainfall and reference evapotranspiration (ET_o) data were collected from the Climate Engine application to determine the water requirements of crops selected for cultivation(ClimateEngine.Org, n.d.). GridMET-4km-daily was selected as the data set and 4km (1/24-deg) was selected as the Computation Resolution. GridMET is a collection of daily surface meteorological data characterized by high spatial resolution (4 km, 1/24 degree), spanning the contiguous United States from 1979 to the present day with a small delay in availability. These data serve as important inputs for ecological, agricultural, and hydrological models and are updated daily in this application. The recommended nomenclature for these data is gridMET, but they are alternatively recognized under the name cite METDATA. The resulting gridded surface meteorological data were validated against a large network of weather stations, including RAWS, AgriMet, AgWeatherNet, and USHCN-2. These data were analyzed to provide information on the performance a daily water balance for these crops (ClimateEngine.Org, n.d.).

Accurate estimation of ET_o is crucial for various aspects of effective irrigation management, including crop production, water resources management, irrigation scheduling, and environmental assessment. ET_o is therefore recognized as a very useful indicator for ensuring optimal irrigation practices (Allen & Pereira, 2006). Reference evapotranspiration (ET_o) can be calculated based on meteorological data and is considered a climatic parameter (Allen & Pereira, 2006).

3.2.5 Calculations

3.2.5.1 Water balance calculations

While calculations were made to determine the daily data for 30 years, only the growth periods of the selected plants, from planting to harvest, were taken into account.

In this study, the K_c values in water balance calculations during the year only cover the growing periods for three plants. K_c values for the times outside the growing season were included in the calculations as zero.

ET volume was calculated.

$ET = K_c \times Et_o \times A$................3

Where A is the area within the high tunnels where the cultivated plants are planted. In this study, $A = 178.4M^2$.

Et_o: Reference evapotranspiration

K_c: Crop coefficient

Equation 2 was considered when calculating the water requirement of the plant.

States	Av. Annual Precipitation (inch/year)	Precipitation (St. Dev.)	Growing Season Percentage P %	Av. ET Tomatoes Depth (inch/year)	Av. ET Cucumber Depth (inch/year)	Av. ET Beets Depth (inch/year)
AR	52	9.69	42	30	23	24
CA	25	8.97	11	37	28	29
CO	14	3.10	62	33	26	27
GA	48	8.21	43	31	24	25
IL	38	6.80	52	27	21	22
KY	54	8.19	43	26	21	21
MI	34	4.04	50	23	19	19
MO	44	6.98	56	29	23	23
SD	19	3.96	66	31	25	24
TX	33	8.10	49	37	29	30
VT	47	6.02	48	20	17	16
WA	68	10.78	17	23	19	18

Table (4) Average annual precipitation and ET depth for three plants (inch/year). For Et depth values ranging from (37 - 20) for tomatoes, (29 - 17) for cucumbers, and (30 - 16) for beets, with values varying from region to region.

3.2.5.2 Cumulative Runoff (gal)

Runoff from the high tunnel was calculated by multiplying the daily precipitation depth by the roof area.

3.2.5.3 Available water volume in the tank (gal)

Available water volume in the tank values represents the amount of water remaining in the tank after the rainwater collected from the roof meets the water needs of the cultivated plants. A series of calculations were performed to obtain this data.
These are as follows.

3.2.5.4 Volume in Tank after ET (gal)

The daily water requirement of the plants was subtracted from the daily rainfall. These values are then calculated cumulatively since the tank serves as a storage area and the remaining water is expected to be used for the following days.

3.2.5.5 Extra Water Needed Plants (gal)

In this process, calculations were made considering both the actual volume in the tank and the ET volume of the plant. Calculations were made by subtracting the volume of water collected in the tank from the ET volume values. This calculation was made to determine the water requirement of the plants when their water needs could not be met from the tank. In other words, this value shows the amount of drinking water that should be used for irrigation.

3.2.5.6 Tank Overflow (gal)

The calculations involved deducting the water requirements during the plant growth periods from the daily water obtained from precipitation and stored in the tank. On days outside the growing season, rainwater from the roof is assumed to be collected directly into the tank and the calculations start by including the amount of this water available in the tank at the beginning of the growing season, without considering the impact of external environmental factors.

3.2.5.7 Irrigation from Tank (gal)

Using 7 different tank sizes to store the harvested rainwater, the amount of irrigation from the tank was calculated based on the water requirements of the plants. This calculation was obtained by subtracting the additional water requirement values from the daily ET volume of the plants.

3.2.5.8 Irrigation Needs Met from RWH (%)

The 30-year averages of Tank Irrigation values were calculated according to the different tank sizes, which represent the percentage of the plant’s water needs.

It was calculated.

Irrigation needs met from RWH= $\frac{Avarage\ Irrigation\ from\ tank(gal)x100}{Avarage\ ET\ Volume\ of\ plant(gal/day)}$

3.2.5.8.1 Irrigation replacement (%)

Irrigation Replacement (IR) was calculated yearly

IR= $1-\frac{ET\ Volume\ of\ plant(gal)-Irrigation\ from\ tank(gal)}{ET\ Volume\ of\ plant(gal)}$……….4

3.2.5.8.2 Runoff Reduction (gal)

Runoff reduction (RR) was calculated yearly

RR= $\frac{Annual\ high\ tunnel\ roof\ runoff(gal)-Tankoverflow(gal)}{Annual\ high\ tunnel\ roof\ runoff(gal)}$………….5

3.2.5.8.3 ET Depth (gallon)

ET Depth = $\frac{Annual\ Precipitation\ (gal)}{Annual\ ET\ Crop\ (gal)}$………….6

3.2.5.9 Cost Calculation

The cost calculation was divided into three parts; the first is the annual tank cost, the second is the cost of water used for irrigation for three plants, and the third part is the amount of money that can be saved.

A 2012 study at Iowa State University puts the cost of a RWH system applied to a high tunnel roof, including gutters, storage tanks and an electric pump, at around \$1200. (M. Bartels Rebecca, 2012). Of course, the roof area and the size of the tank used will directly affect this pricing.

3.2.5.10 Tank Cost

The tank cost was calculated by the following equation.

$$A_c = P_v \frac{i(1+i)^N}{(1+i)^N - 1}$$

where A is annualized tank cost, i is the interest rate, P is principal/present value, and N is tank life (S. Park Chan, 2007).

The assumed values for each variable are interest rate of 3%, P was calculated at $1 per gallon and varied by tank size, and tank life was assumed to be10 years.

3.2.6 Statistical Analysis

Statistical analysis was performed using Minitab 21 (Minitab LLC, State College, PA). This analysis includes annual average data analysis, average, standard deviation, boxplot, correlation matrix, scatterplot, and heat maps.

3.3 Results

In this project, rainfall patterns over 30 years in 12 states were studied and how much water would be stored from a high tunnel roof area was calculated using 7 different tank sizes. ET_o data was collected for the same regions and time period and water balance was calculated for three crops to be grown. To determine the effectiveness of the RWH technique regionally, it was tried to observe which tank size would be more effective region by region in irrigation as an additional water source instead of potable water. The RWH technique was also used to analyze the percentage of runoff reduction for the same tank sizes. The study evaluated the percentage of annual water supplied by the tank for each plant species and examined the extent to which runoff from rainfall was reduced using the RWH approach. It also evaluated the amount of overflow according to the size of the tanks and the potential for potable water irrigation when the water in the tank is not sufficient for irrigation. Finally, a cost-effectiveness assessment was made by calculating the amount of cost savings that could be achieved by replacing potable water irrigation with RWH. In this section, the installation costs of the RWH system and the tank cost were calculated to determine the amount of money that could be saved.

3.3.1 Annual Precipitation and ET_o (inches)

In states other than KY, VT, and WA, ETo is higher than the average annual rainfall. For AR, these values are close to each other (Figure 10).

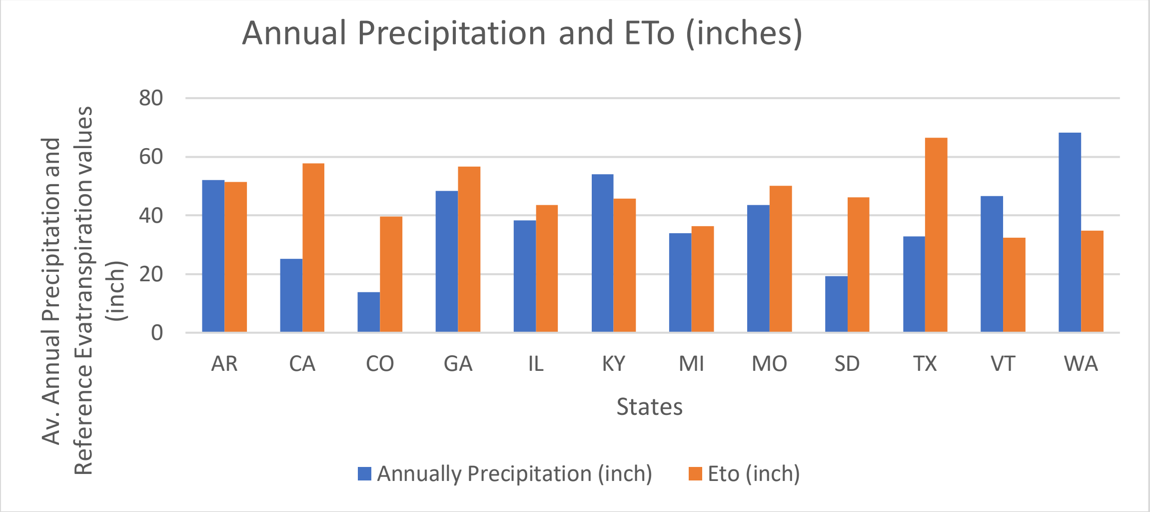

Figure (10) The blue columns show daily precipitation values, and the orange columns show reference evapotranspiration. State names are displayed on the horizontal axis, with precipitation amounts in inches on the vertical axis (0 to 80 inch).

While examining the effect of using rainwater accumulated in the tank for irrigation, the quantity of rainfall during the crop-growing period is as crucial as the amount of rainfall received by the region. California has the lowest percentage of growing season precipitation at 11%, while South Dakota has the highest at almost 66% (Figure 11).

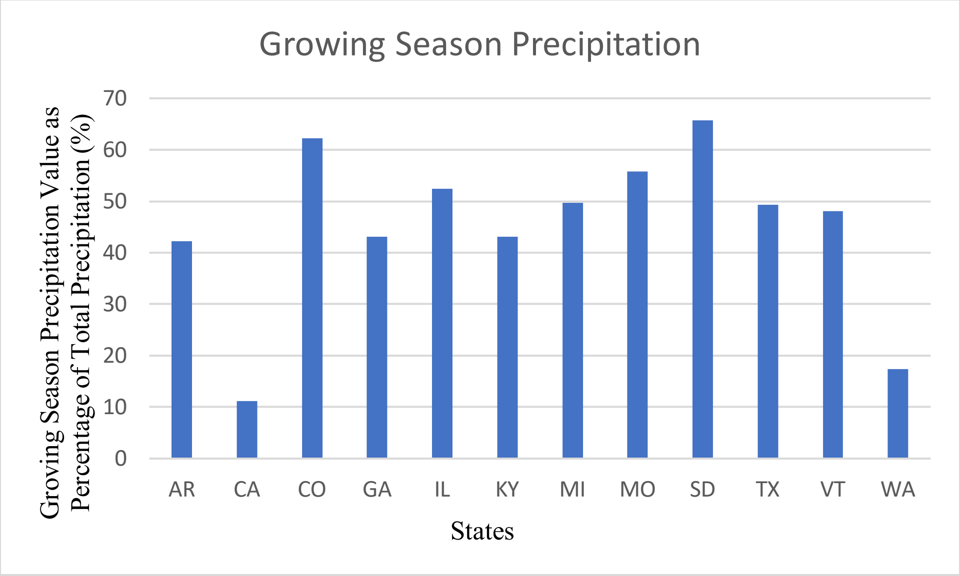

Figure (11) Percentage of precipitation falling during the growing season.

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3.3.2 Irrigation Replacement of Plants (Tomatoes, Cucumber, and Beets)

Irrigation Replacement varied from very low across all tank sizes in states like Colorado to very high for tank sizes 1,000 gallons and above for states like Vermont (Figures 12, 13, and 14).

A box and whisker plot, also known as a boxplot, provides a visual summary of the distribution of a dataset. It includes the median (50th percentile) and the quartiles (25th and 75th percentiles), as well as the minimum and maximum values. The box in the plot represents the middle 50% of the data, with the bottom of the box indicating the first quartile (25th percentile) and the top of the box indicating the third quartile (75th percentile). The line inside the box represents the median, which is the 50th percentile of the data (Xianjun Dong, 2012). Asterisks show outliers.

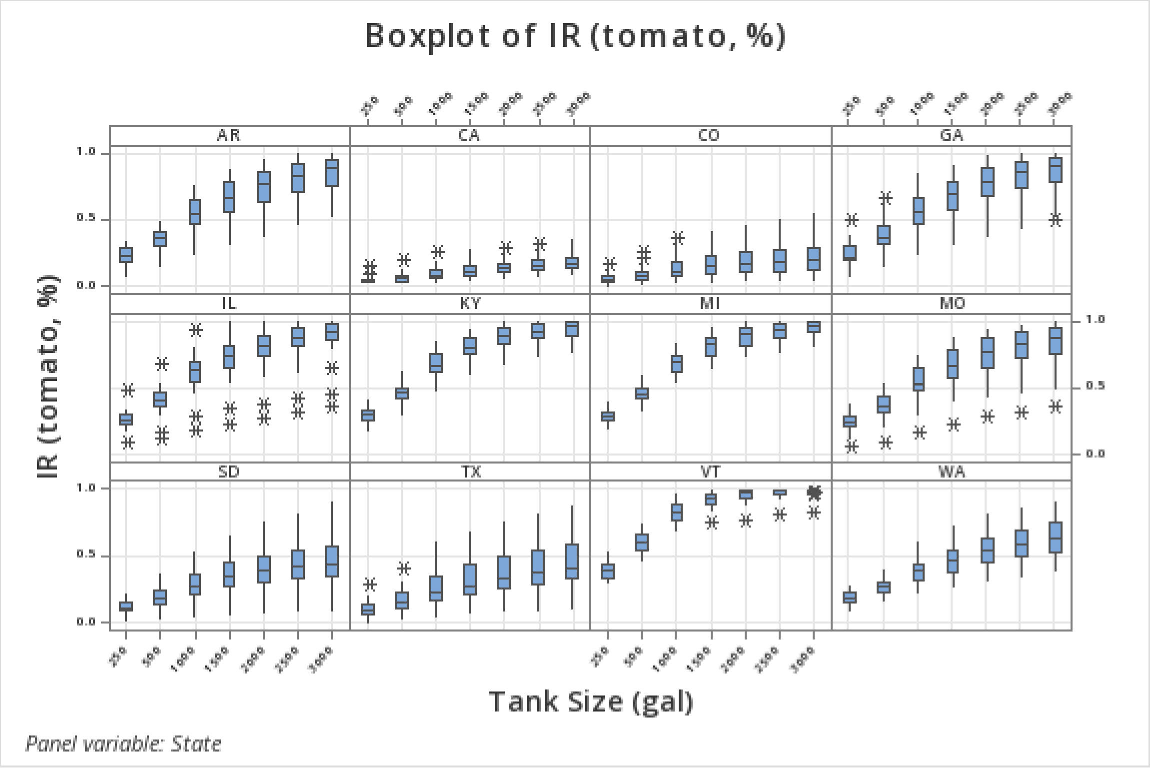

Figure (12) Tank sizes are shown in gallons on the horizontal axis and irrigation replacement rates for tomatoes in percentages on the vertical axis (0-1). The Whisker box displays the changes in the IR (%) with respect to tank sizes. Asterisks represent data outliers in the IR (%) changes in the 30-year data.

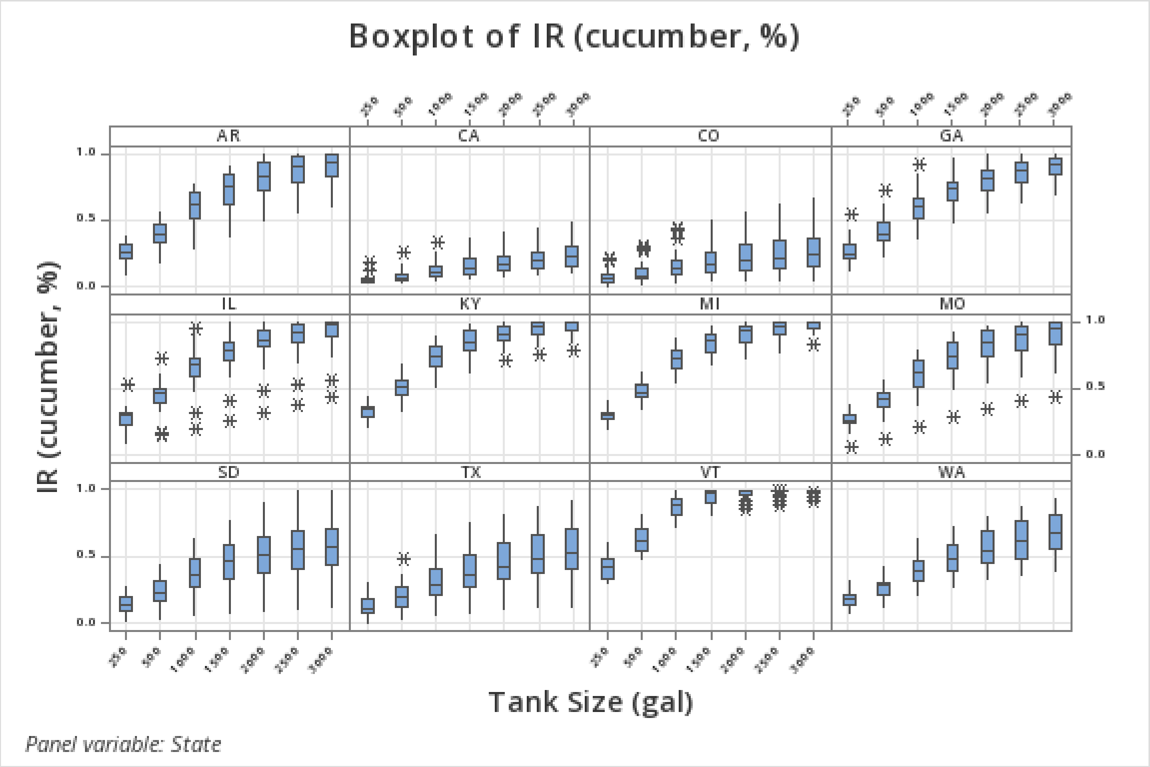

Figure (13) Tank sizes are shown in gallons on the horizontal axis and irrigation replacement rates for cucumber in percentages on the vertical axis (0-1). The Wisker box displays the changes in the IR (%) with respect to tank sizes. Asterisks represent deviations in the IR (%) changes in the 30-year data.

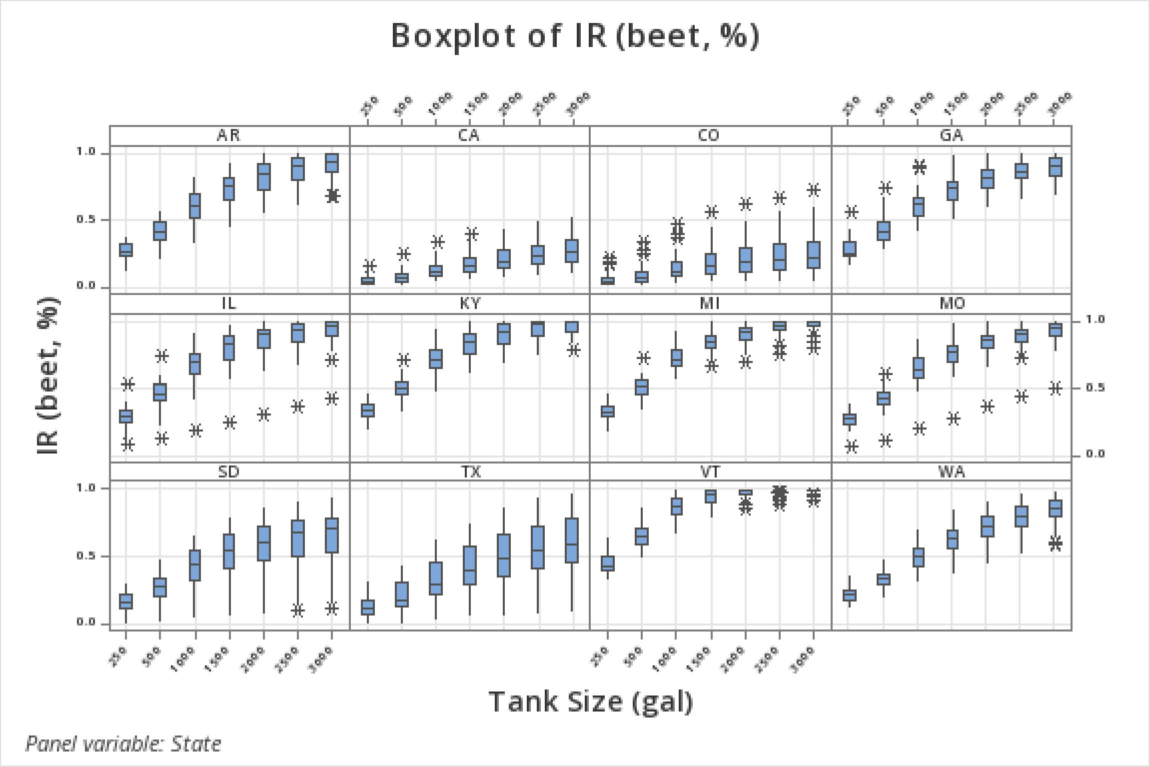

Figure (14) Irrigation replacement (%) boxplot for beets according to state and seven different tank sizes. Tank sizes are shown in gallons on the horizontal axis and irrigation renewal rates for cucumber in percentages on the vertical axis (0-1). The Wisker box displays the changes in the IR (%) with respect to tank sizes. Asterisks represent deviations in the IR (%) changes in the 30-year data.

For all three plants, the IR (%) value starts to change from blue to red on the heat map after the 1000-gallon tank size. In general, the color change between the 1500 and 2500-gallon tanks indicates minimal change over 1,500 gallons (Figures 15, 16, and 17). For all three crops, over 50% irrigation replacement was achieved over 1,500 gallons. However, this was highly variable by state (Figures 12, 13, and 14)

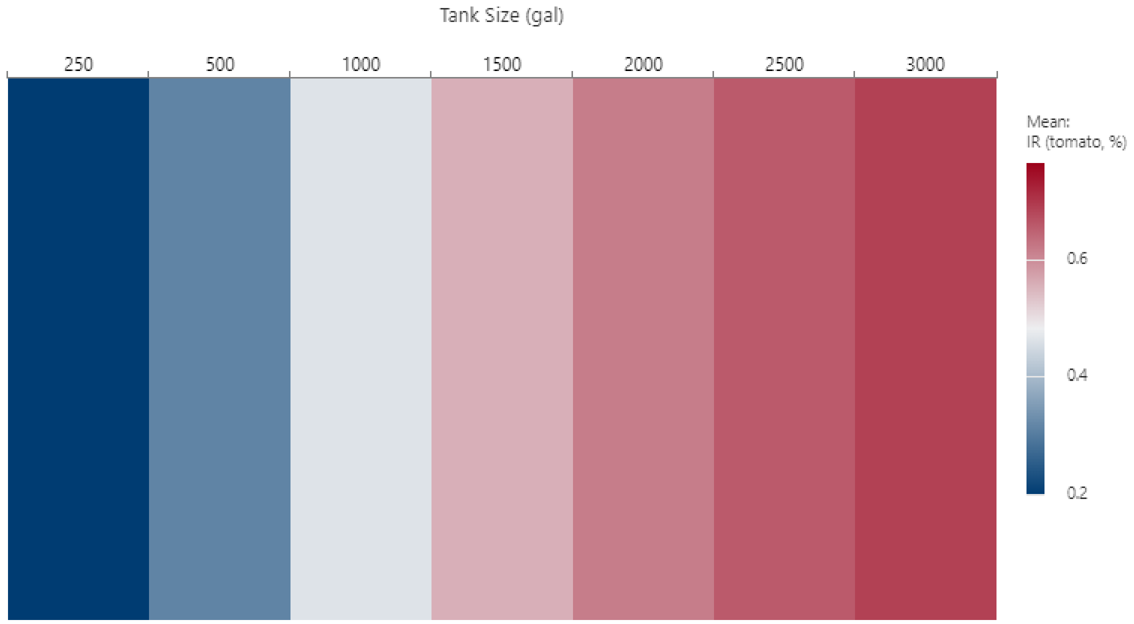

Figure (15) Heat map by tank size in light blue indicating low irrigation replacement and dark red indicating high irrigation variation. Each rectangle represents the average irrigation variation by tank size for tomatoes and the average of the data from all locations. Percent irrigation change is on the vertical axis and tank sizes in gallons are on the horizontal axis. The color change varies in percentage from dark blue to light blue depending on the value increase in the range 0-0.5. Likewise, the range from light red to dark red covers a value range of 0.5-1.

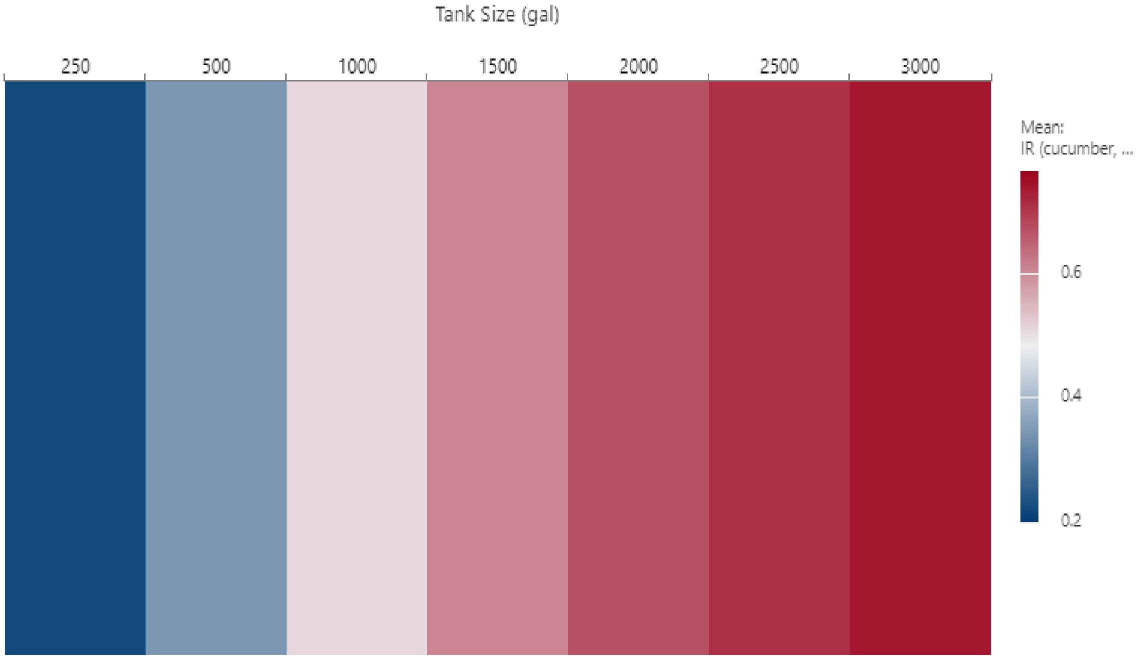

Figure (16) Heat map by tank size in light blue indicating low irrigation variation and dark red indicating high irrigation variation. Each rectangle represents the average irrigation change for cucumbers and the average of the data from all locations. Percent irrigation change is on the vertical axis and tank size in gallons is on the horizontal axis. The color change is classified from dark blue to light blue based on the increase in the 0-0.5 value range and from light red to dark red based on the increase in the 0.5-1 value range, respectively.

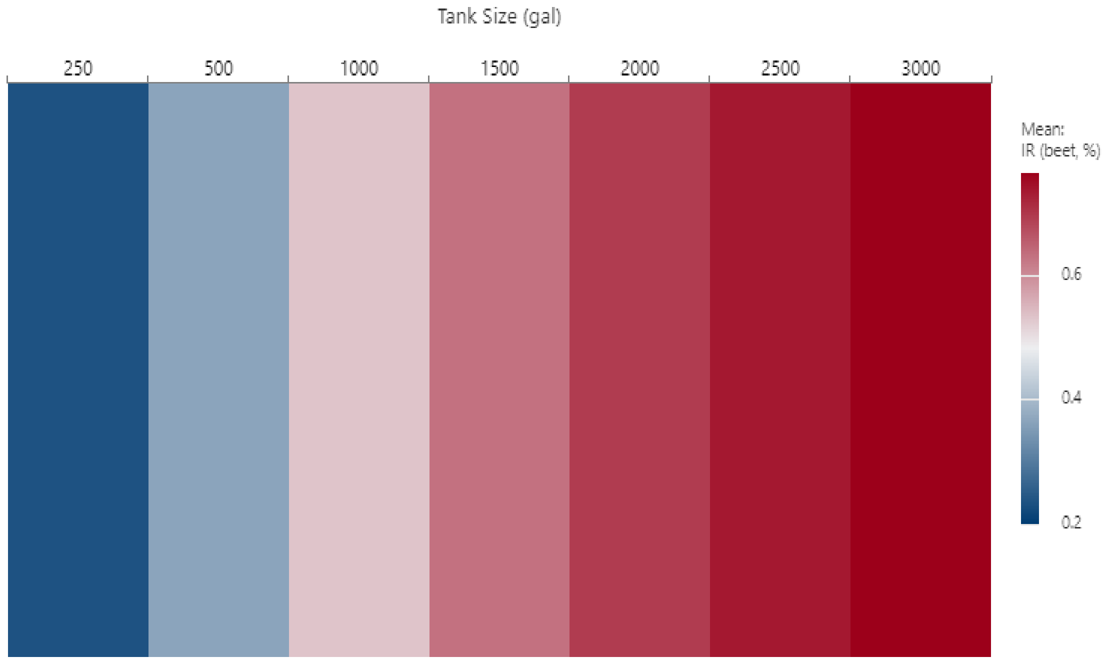

Figure (17) Heat map by tank size in light blue showing low-rate irrigation replacement and deep dark red, showing high irrigation replacement. Each rectangle represents the average irrigation replacement for beets and the average of the data from all locations. The percentage of irrigation replacement is on the vertical axis and tank dimensions in gallons are on the horizontal axis. The color change is classified from dark blue to light blue based on the increase in the 0-0.5 value range and from light red to dark red based on the increase in the 0.5-1 value range, respectively.

3.3.3 Tank sizes and potable water irrigation for plants.

As the tank size increases, the quantity of potable water used for irrigation decreases. However, while this decreasing trend is significant in some states, it is comparatively lesser in others such as CA, CO, SD, and TX (Figure 18).

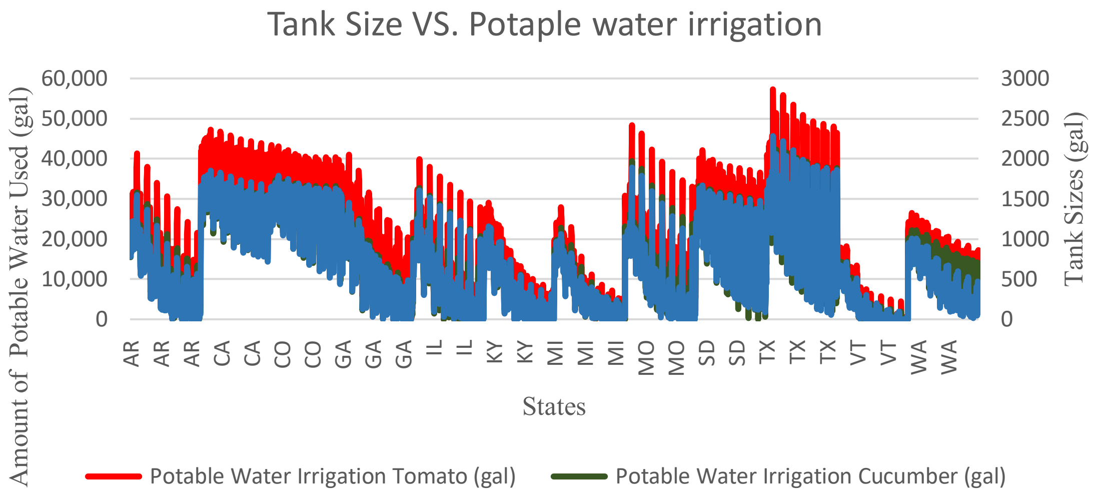

Figure (18) Tank sizes and potable water irrigation for plants. Potable water irrigation quantities in gallons on the right vertical axis, tank sizes on the left vertical axis, and state names on the horizontal axis.

The rate of meeting the seasonal irrigation needs of all three plants from harvested rainwater (RWH) tanks varies depending on the selected regions and tank sizes. Calculations are shown for the minimum value corresponding to a 250-gallon tank and the maximum value corresponding to a 3000-gallon tank. These values are generally highest in tomatoes and lowest in beets. This is mainly due to the longer growing season and the higher irrigation requirements of tomatoes. The opposite is true for beets. As a result, if we talk about each state for itself, the rainwater collected is the same for every plant. The percentage utilization of this collected water is directly related to the water needs of the plants. The two states with the lowest values are CO and CA (around 3% and 20%) (Table 5, Figure 19).

	Irrigation needs met from RWH (%)		
States	Tomatoes (min-max)	Cucumber (min-max)	Beets (min-max)
AR	21-81	19-67	20-70
CA	3-17	3-17	3-21
CO	5-21	5-21	4-20
GA	23-85	20-70	22-71
IL	25-87	22-73	23-75
KY	29-93	26-77	26-77
MI	28-95	24-80	26-79
MO	22-82	20-69	21-72
SD	11-45	11-46	13-50
TX	10-44	9-42	10-45
VT	39-100	34-83	37-81
WA	19-64	15-56	18-67

Table (5) Irrigation needs met from RWH (%) for three plants. Depending on the size of the tank and the selected locations, the percentage of the total water needs of the cultivated plants met from rainwater accumulated in the tank (3%-100%).

3.3.4 Irrigation met by RWH technique.

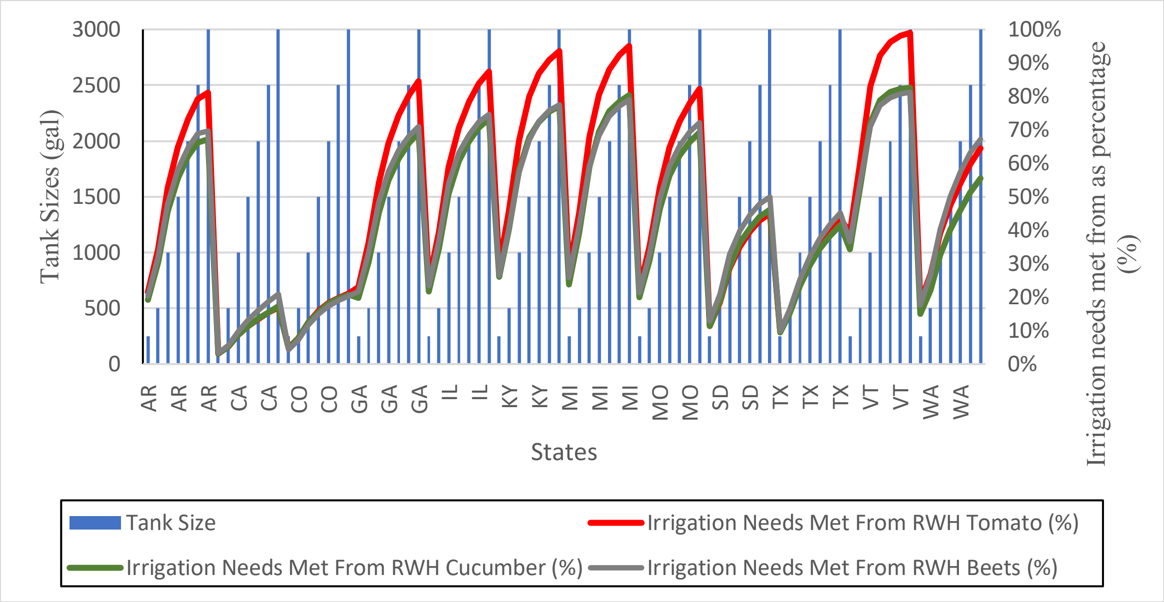

Figure (19) In this graph, the values on the left vertical axis show the tank sizes (250-3000gal), and the values on the right vertical axis show the average one growing season irrigation amount provided from the tank where the rainwater is stored in percent (0-1), and the state names on the horizontal axis.

3.3.5 Average Annual Runoff Reduction Achieved Using the RWH Technique by Tank Size and State (%)

The values of RR (%) according to tank sizes do not show much variation among states, except for CA, CO, SD, and TX. Furthermore, the impact of the increase in tank sizes on RR (%) in these states tends to increase at a slower rate as tank sizes increase (Figure 20).

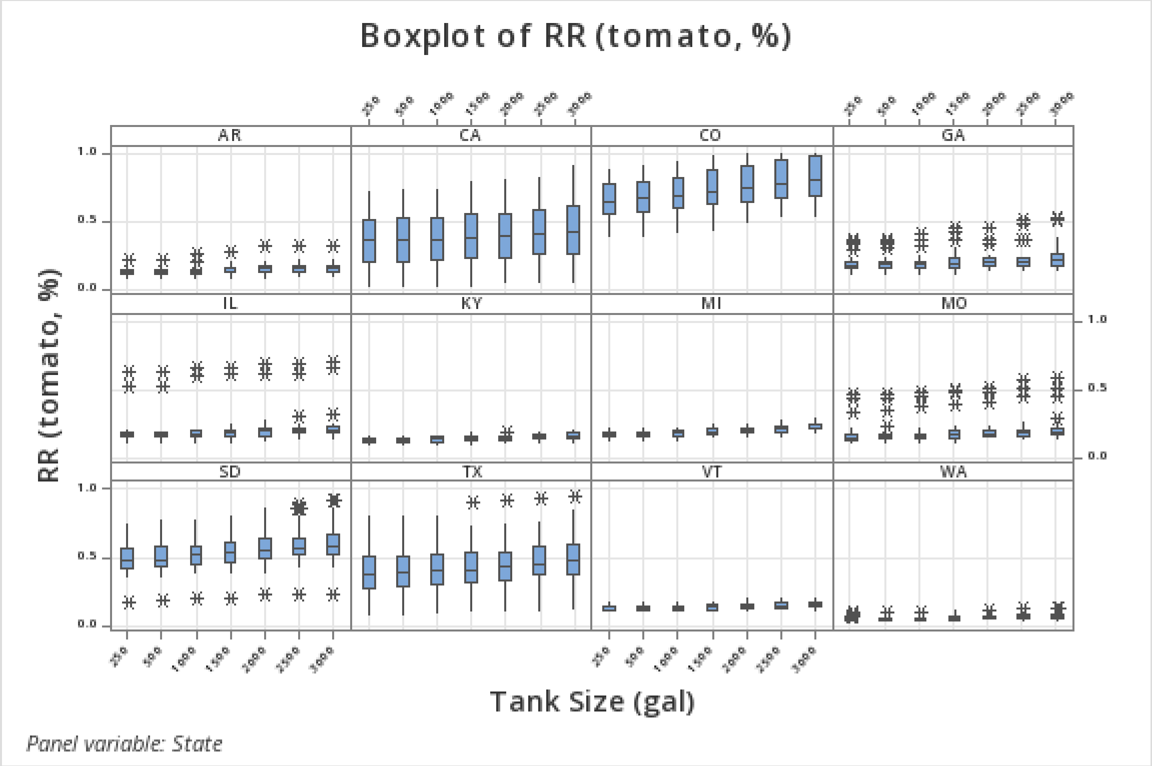

Figure (20) Tank sizes are shown in gallons on the horizontal axis (250-3000 gal) and runoff reduction rates for cucumber in percentages on the vertical axis. The percentage varies between 0-1. The Wisker box shows the changes in RR (%) by tank size. For each state, there is a general increase in the change in RR (%) as the tank size increases. However, this increase is very small in some states. Asterisks represent deviations in RR (%) changes over 30 years of data.

3.3.6 Average Runoff Reduction and Overflow with RWH technique by Tank Size

It occurs after the overflow tank is filled and exhibits an inverse relationship with RR. While CO and SD experience the least overflow, the RR value is highest for these two states (Figure 21).

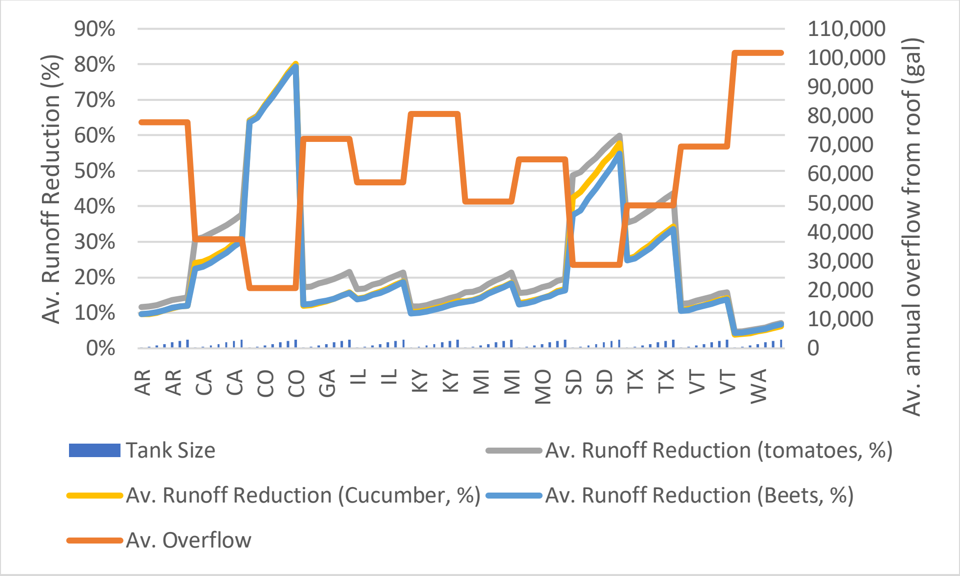

Figure (21) Average runoff reduction (%), (0.10-0.90) and av. annual overflow from the high tunnel's roof (gal) (10000-110000). Tank sizes (250 gal to 3000 gal).

3.3.7 Effect of RWH Tank Dimensions on Runoff Reduction

In the RR heatmap of the tomato plant with the longest growing period, the RR (%) value initially starts at about 0.26, which is considered intermediate, and gradually transitions from light blue to red with subtle tonal shifts. However, there is no significant variation in tone depending on tank dimensions. On the other hand, a light red color was observed in the heat map of the beet plant with the shortest growth period. It starts with a near-dark blue hue indicating the lowest RR (%) of 0.21 and gradually exceeds the midpoint value of 0.26 with smooth tonal changes (Figures 22, 23, and 24). While the difference across tank sizes is apparent, the difference by crop is striking. This indicates that crop type, and consequently, water demand is a significant factor for runoff reduction.

3.3.7.1 Heatmap of RR (tomato, %), RR (cucumber, %), RR (beet, %)

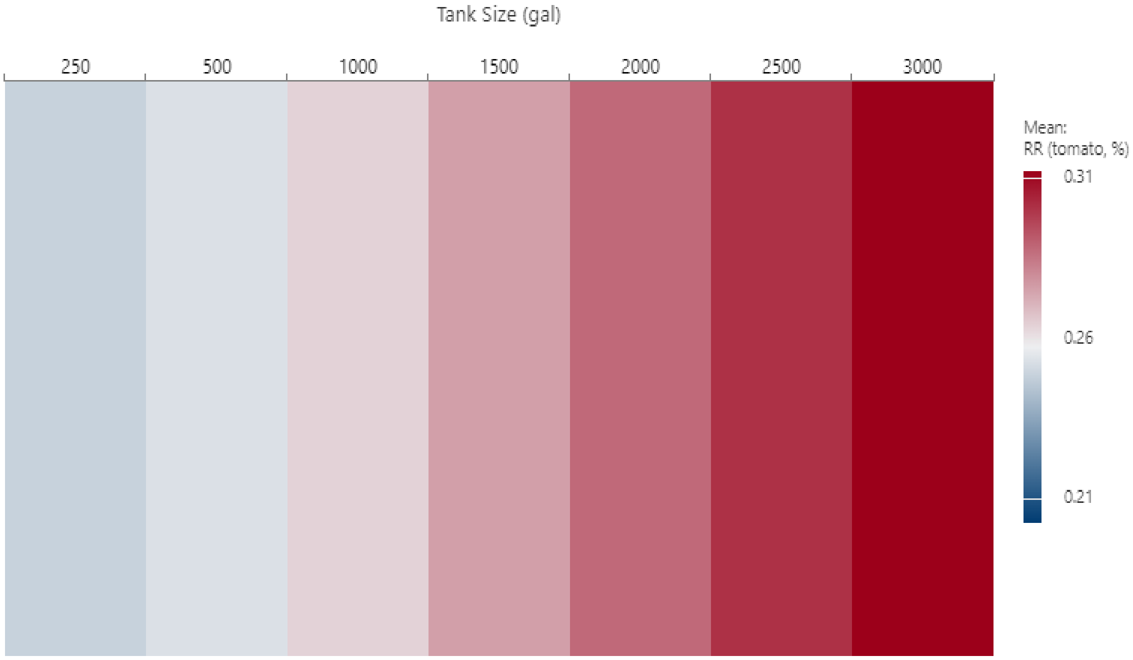

Figure (22) Heat map of tomatoes by tank size in light blue showing low-rate runoff reduction and deep dark red, showing high runoff reduction. Each rectangle represents the tank sizes and the average of the data from all locations. The percentage of runoff reduction is on the vertical axis (0.21-0.31 and tank dimensions are in gallons is on the horizontal axis (250-3000).

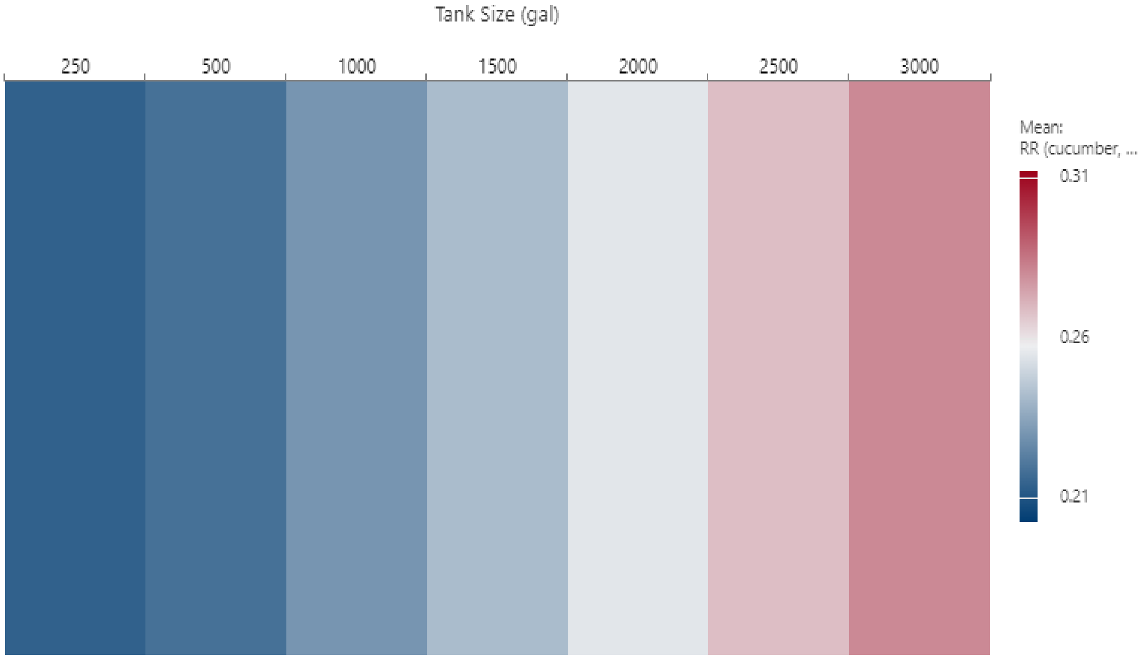

Figure (23) Heat map of cucumber by tank size in light blue showing low-rate runoff reduction and deep dark red, showing high runoff reduction. Each rectangle represents the tank sizes and the average of the data from all locations. The percentage of runoff reduction is on the vertical axis (0.21-0.31 and tank dimensions are in gallons is on the horizontal axis (250-3000).

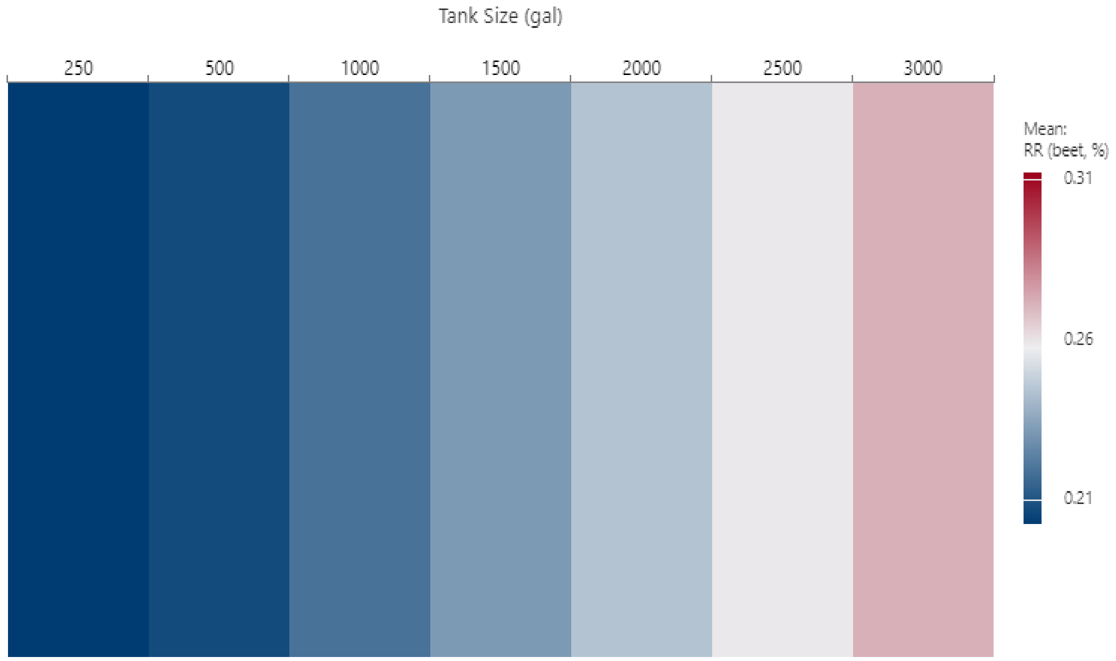

Figure (24) Heat map of beets by tank size in light blue showing low-rate runoff reduction and deep dark red, showing high runoff reduction. Each rectangle represents the tank sizes and the average of the data from all locations. The percentage of runoff reduction is on the vertical axis (0.21-0.31 and tank dimensions are in gallons is on the horizontal axis (250-3000).

3.3.8 Correlation Matrix between Evapotranspiration Depth, Runoff Reduction, Irrigation Replacement, Tank Sizes, and Precipitation

Runoff reduction is strongly negatively correlated with precipitation but not strongly correlated with tank size. This indicates that if you are in an area with high precipitation, runoff reduction will be challenging to achieve, simply by relying on increasing tank size. However, runoff reduction is relatively strongly correlated with ET depth, which indicates that having a way to use the water between storm events is a more effective method to effectively reduce runoff. Conversely, irrigation replacement has a medium, positive correlation with tank size, which indicates that increasing tank size for irrigation replacement does matter. Irrigation replacement is also positively correlated with precipitation but has a higher correlation with tank size which indicates that reduced precipitation can be overcome through increasing tank size (Figures 25, 26, and 27).

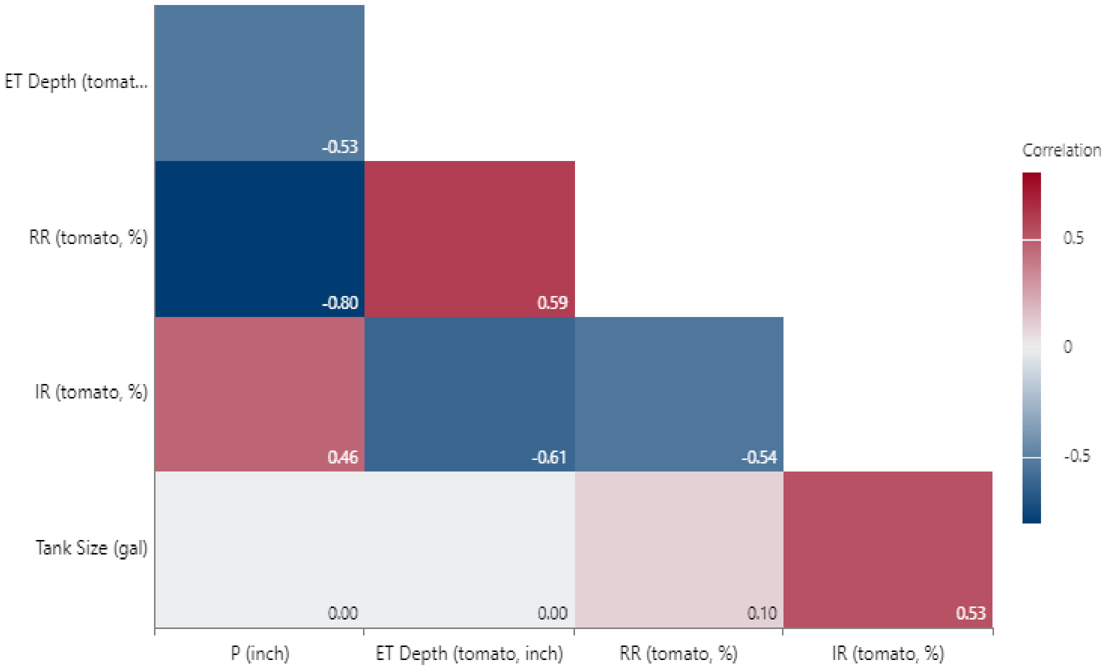

Figure (25) This figure shows that for tomatoes cases compared from light blue to dark blue increase in inverse proportion (-0.5-0). Indicates that the relationship between cases increases at the correct rate compared to light red to dark red (0-0.5).

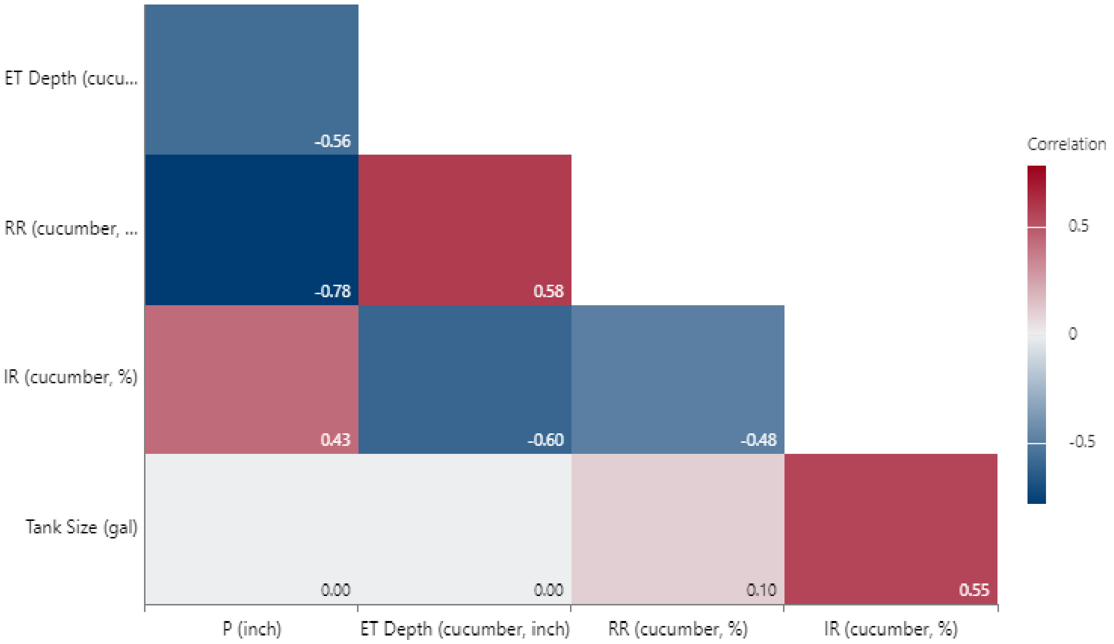

Figure (26) This table shows that for cucumber cases compared from light blue to dark blue increase in inverse proportion (-0.5-0). Indicates that the relationship between cases increases at the correct rate compared to light red to dark red (0-0.5).

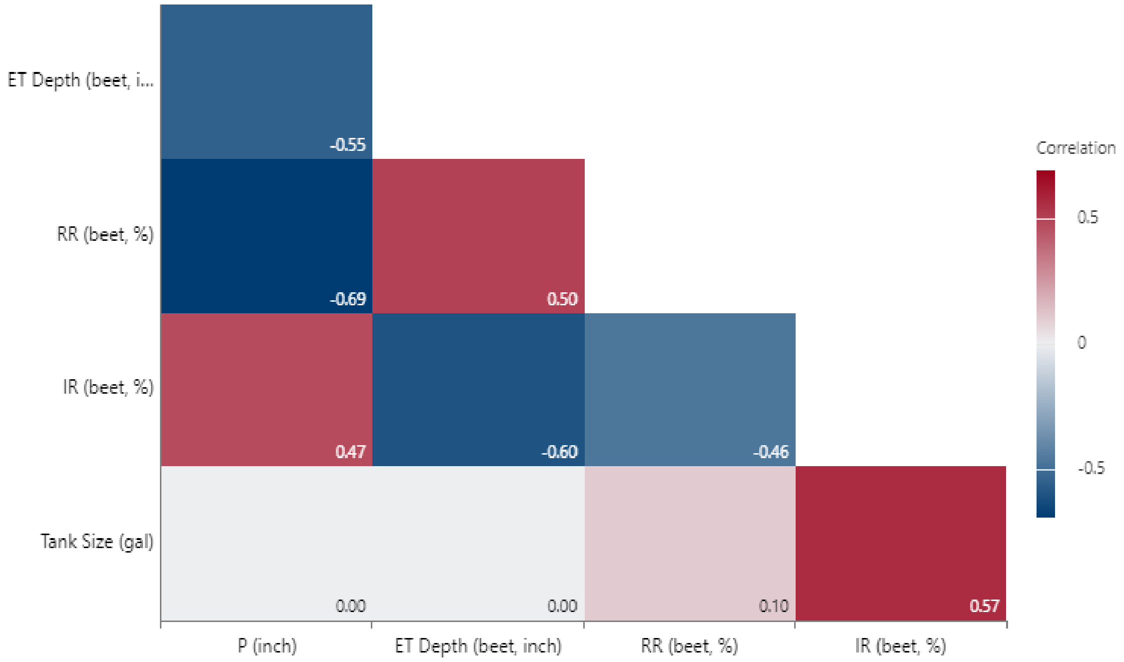

Figure (27) This table shows that beet cases compared from light blue to dark blue increase in inverse proportion (-0.5-0). Indicates that the relationship between cases increases at the correct rate compared to light red to dark red (0-0.5).

3.3.9 Relationship between Irrigation replacement and Precipitation/Evapotranspiration of crop

In the comparison of IR (%) and P/ET, the IR (%) value in 250 and 500-gallon tanks cannot reach 100% for each P/ET value. As the tank size increases, the P/ET value at which the IR (%) reaches 100% decreases (Figure 28).

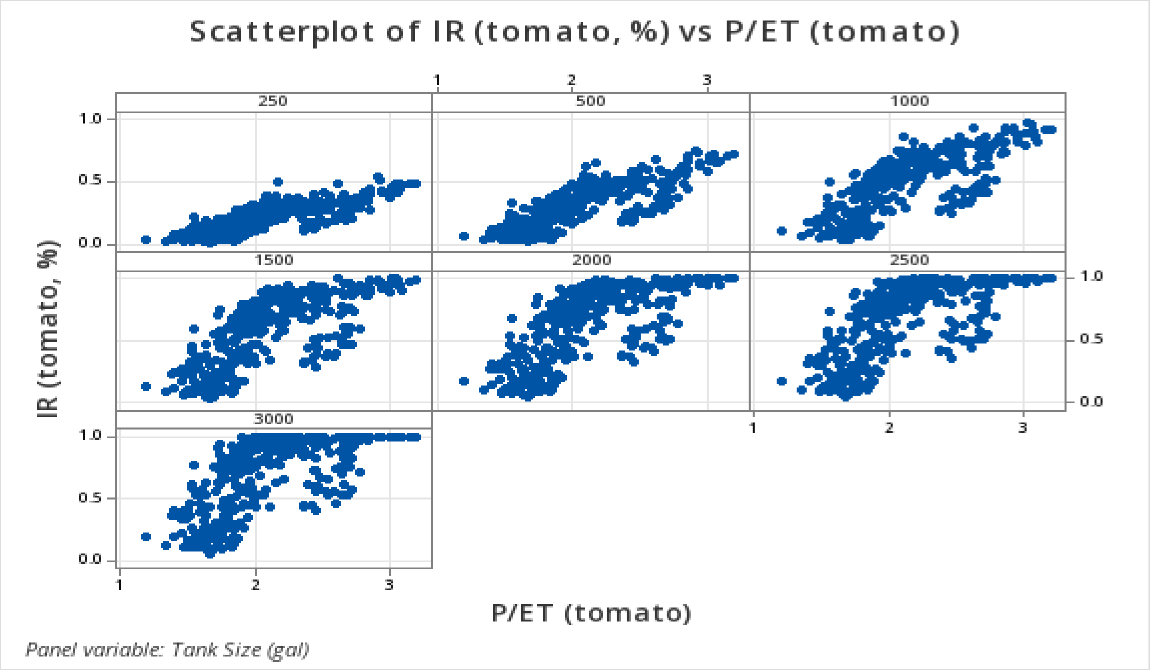

Figure (28) IR vs P/ET tomatoes. Each rectangle represents the tank size, with the vertical axis representing IR (%) (0-1) and the horizontal axis representing P/ET (1-3).

In the comparison of RR (%) and P/ET, the RR (%) value reaches 100% after the 1000-gallon tank. However, for each tank size, there is no significant trend observed in the relationship between these two values (Figure 29).

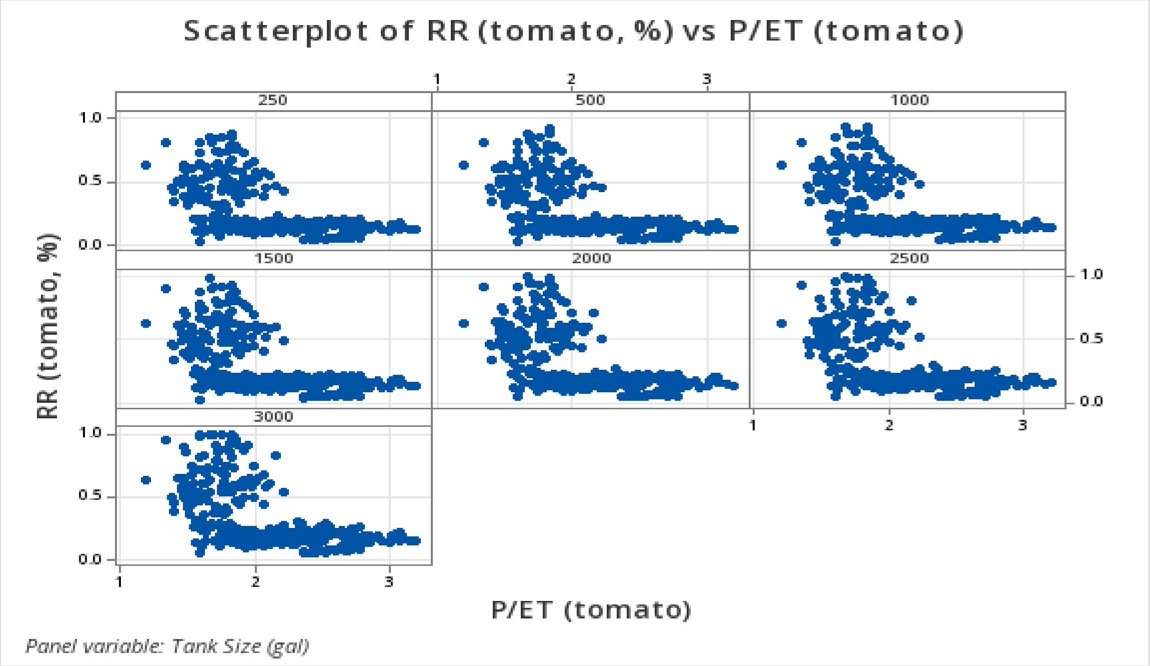

Figure (29) RR vs P/ET tomatoes. Each rectangle represents the tank size, with the vertical axis representing RR (%) (0-1) and the horizontal axis representing P/ET (1-3).

3.3.10 Tank Cost

The lowest cost is the 250-gallon tank at 29$/year and the highest cost is the tank from around 350$/year to 3000 gallons, annually (Figure 30).

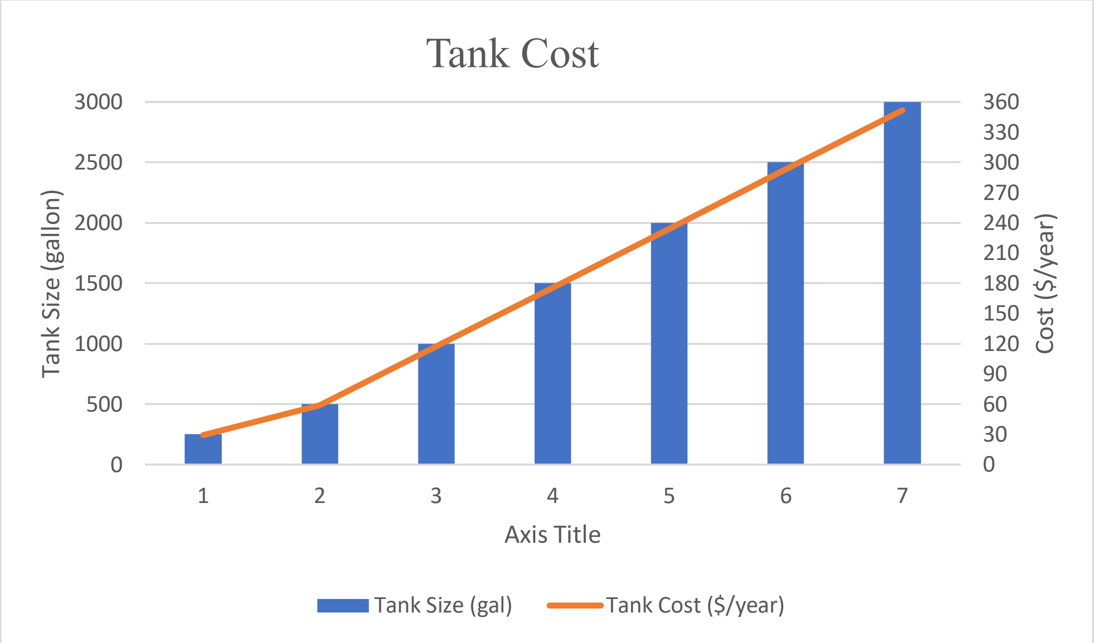

Figure (30) Tank cost annually between around 30$ and 350$.

3.3.11 Potable Water Irrigation Cost

When calculating the cost of potable water for irrigation, local municipal water costs of all selected regions were considered. In addition, non-residential water cost was considered for each region. It is assumed that all irrigation needs are met with potable water, and expenses such as maintenance expenses and water connection expenses are not considered. Multiplying "Water cost per gallon" by "Av ET_o Crops" and adding "Fixed meter charge" multiplied by "Growing period (months)", we get the total cost of using potable water to irrigate tomatoes, cucumber, and beet. Here, the growing time was generally accepted as six months for all states, and the irrigation cost was calculated by region for those three plants.

States	Fixed Meter Charge (per month)	Incremental Cost	Unit Volume (gallons)	Water Cost per Gallon
AR, Conway	$ 18.87	$ 2.70	750	$ 0.0036
CA, Madera	$ 23.51	$ 2.41	750	$ 0.0032
CO, Pueblo	$ 26.62	$ 4.78	1000	$ 0.0064
GA, Blakely	$ 35.00	$ 5.50	2000	$ 0.0073
IL, Peoria	$ 21.27	$ 3.34	1000	$ 0.0045
KY, Adair	$ 47.90	$ 6.25	1000	$ 0.0083
MI, Clare	$ 26.85	$ 5.43	750	$ 0.0072
MO, Benton	$ 44.28	$ 3.73	750	$ 0.0050
SD, Stanley	$ 9.25	$ 4.59	1000	$ 0.0061
TX, Hamilton	$ 31.94	$ 3.36	750	$ 0.0045
VT, Washington	$ 45.00	$ 7.50	750	$ 0.0100
WA, Levis	$ 48.45	$ 7.25	1000	$ 0.0097

Table (6) Data for 2022 collected from regional municipalities required for potable water cost calculation. May vary from year to year.

The costs of network water vary according to state. The highest cost of drinking water used for irrigation is attributed to WA and KY, and the costs for tomato cultivation, which has the highest irrigation demand, in these two states are approximately $550 annually. The state with the lowest cost due to drinking water is AR, with amounts ranging between $210 and $240 (Figure 31).

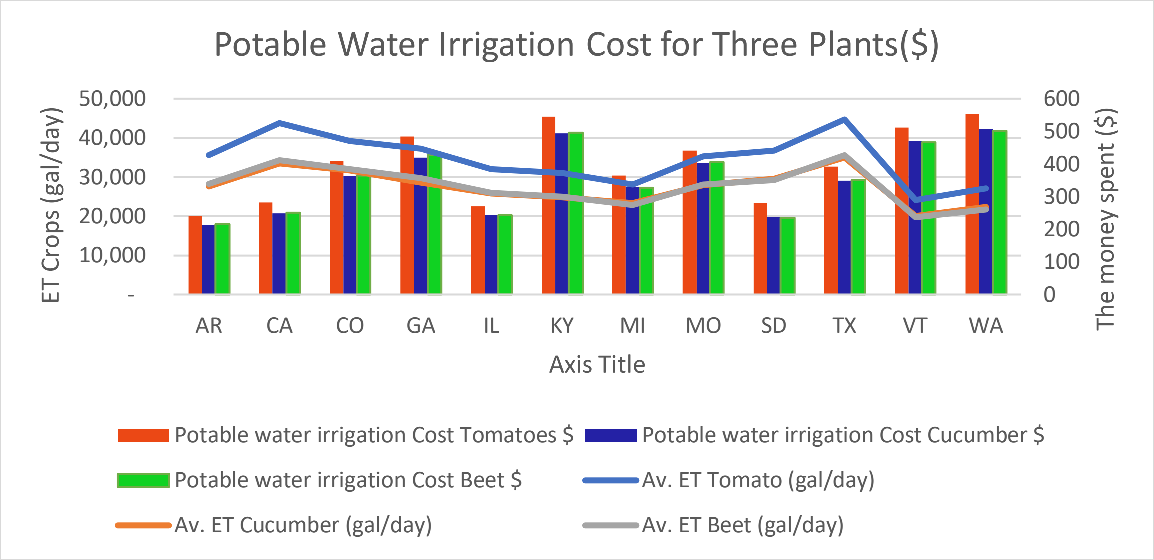

Figure (31) Potable water irrigation cost for three crops: tomatoes, cucumbers, and beets. The left vertical axis shows the daily amount of water required to irrigate the crops in the high tunnel (10gal/day-50gal/day). The right vertical axis shows the cost of irrigation (100-600). The horizontal axis shows selected states. Columns represent tomatoes, cucumbers, and beets in red, blue, and green, respectively. Line graphs represent average ET tomatoes (gal/day), average ET cucumber, and average ET beets in blue, orange, and gray, respectively.

When the tank and maintenance costs of the water obtained through the RWH technique are not included, the states with the highest gains are KY, VT, and GA, in that order. Similarly, when tank costs are added, irrigation water cost savings remain high in these three states compared to others. However, the amount of these savings varies from state to state depending on the size of the tank used. While rainwater harvesting (RWH) has a positive impact as an alternative source of water for irrigation in each state, when tank costs are added, there are no gains in terms of irrigation costs for CA and CO (Figures 32, 33, 34, and 35).

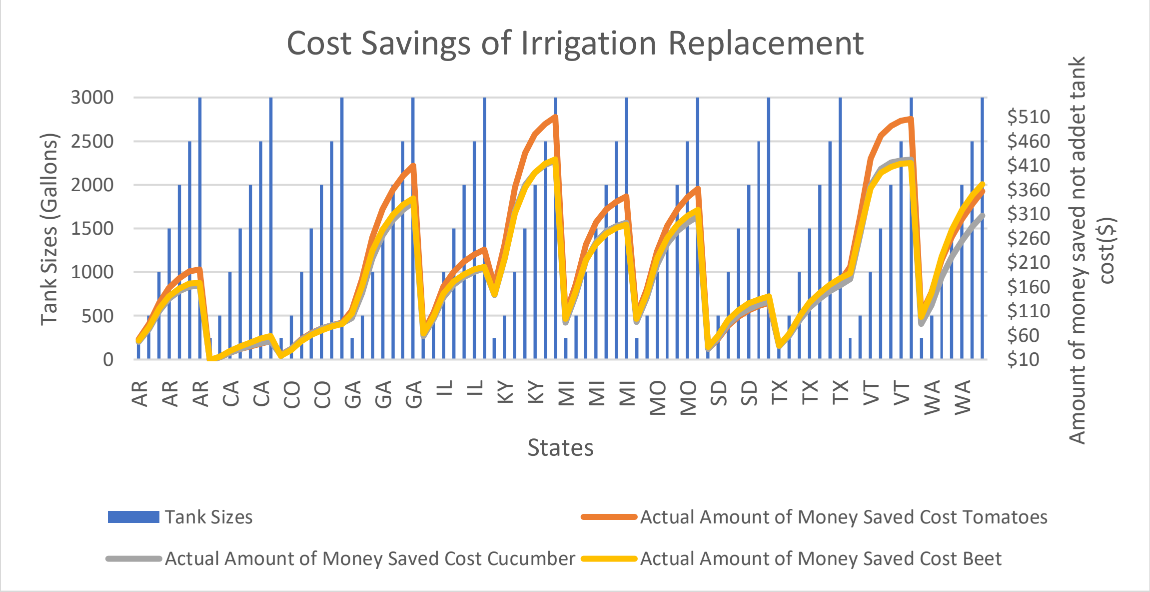

Figure (32) The amount of money saved for irrigation of three crops: tomatoes, cucumbers, and beets. The left vertical axis shows tank sizes (0-3000), and the right vertical axis shows the amount of money we could save by irrigating with water from RWH tanks ($10-$510). Selected states are shown on the horizontal axis. The line graphs show the amount of money saved cost tomatoes ($), the amount of money saved cost cucumbers, and the amount of money saved cost beets in orange, grey, and yellow respectively. Tank cost is not included in this figure.

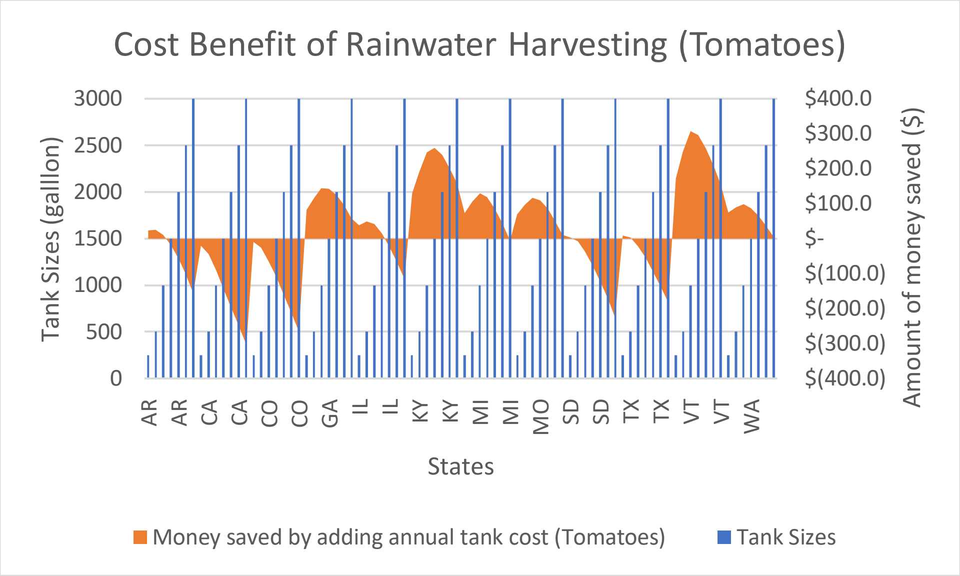

Figure (33) The x-axis on the left displays tank sizes ranging from 250 gallons to 3000 gallons, while the x-axis on the right displays the annual potential cost savings from RWH, ranging from negative to positive $400. The y-axis displays the states that have been selected.

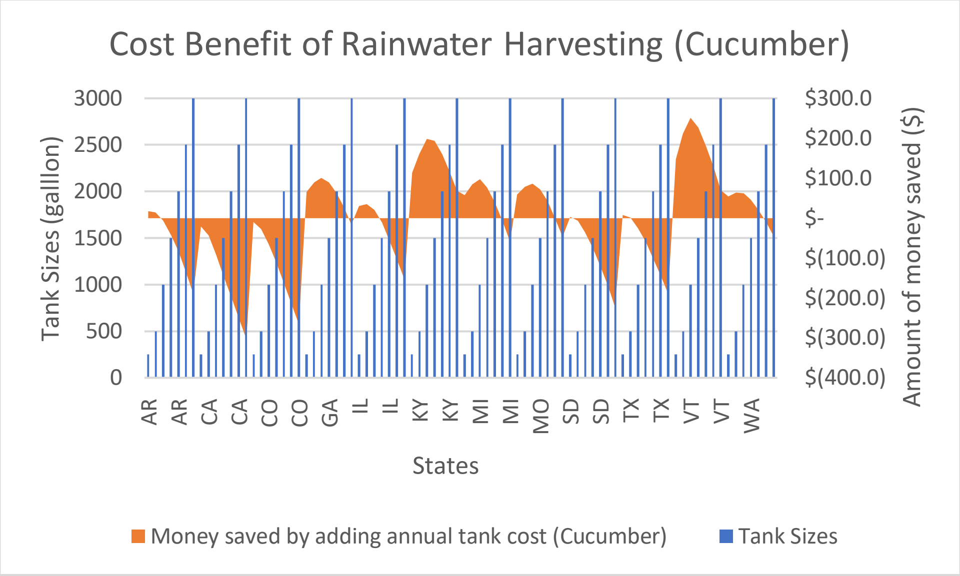

Figure (34) The x-axis on the left displays tank sizes ranging from 250 gallons to 3000 gallons, while the x-axis on the right displays the annual potential cost savings from RWH, ranging from negative to positive $350-$100. The y-axis displays the states that have been selected.

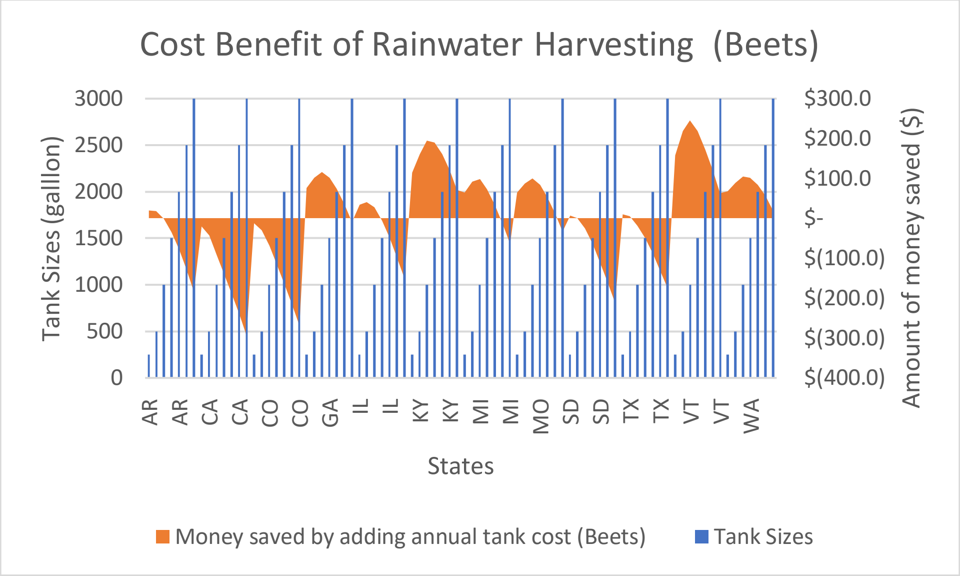

Figure (35) The x-axis on the left displays tank sizes ranging from 250 gallons to 3000 gallons, while the x-axis on the right displays the annual potential cost savings from RWH, ranging from negative to positive $350-$100. The y-axis displays the states that have been selected.

The amount of money saved by irrigation from these tanks was calculated by taking the annual average of the amount of water accumulated in the RWH tank based on 30 years of data and the annual storage costs were subtracted from this value. While calculating 30-

year irrigation cost savings, current drinking water cost values were considered. No calculation was made for each year according to the drinking water values of that year.

3.4 Discussion

In this study, the input comprises daily 30-year precipitation and ET data, the surface area of the high tunnel roof, and various tank sizes used for water storage, while the output consists of tank overflow and the amount of water utilized for irrigation from the tank. During the analysis of these study outcomes, various details were considered, such as the impact of RWH on reducing runoff in the chosen regions, the substitution of RWH for irrigation based on the climatic conditions of the areas, and the correlation between P/ET_c with RR and IR. Lastly, an attempt was made to gain an understanding of the cost-effectiveness of RWH.

One drawback associated with Rainwater Harvesting (RWH) is its reliance on precipitation, a dependency that may be impeded by prolonged periods of dry weather or diminished cumulative rainfall, as highlighted by (Karpiscak., et al 1990). Furthermore, the assessment of RWH effectiveness for agricultural irrigation places importance on the proportion of rainfall occurring during the growing season.

3.4.1 Rainfall and Timing of Growing Season Precipitation

From the analysis of 30 years of data, WA had the highest average annual rainfall of 68 inches, followed by KY with 54 inches, while CO had the lowest with only 14 inches and SD had 19 inches (Figure 10). The percentage of annual precipitation falling during the growing season was highest in SD and CO with 65% and 62% respectively, whereas it was lowest in CA and WA with 11% and 17% respectively (Figure 11).

During the analysis of 30 years' worth of data, it was noted that irrigation replacement (IR) surpassed 90% in nearly all states during certain years. Furthermore, it's worth noting that California and Colorado exhibited the smallest percentages of IR value. Upon further examination of the results based on tank sizes, it was found that irrigation replacement values went up along with larger tank sizes. Generally, rapid escalation occurs from a 250-gallon tank size to a 1500-gallon tank size for all three plants. However, the growth of these values slows down from a 1500-gallon tank size to a 3000-gallon tank size, (Figures 12, 13, and 14). For tanks larger than 1500 gallons, all three plants demonstrated an IR greater than 50%, with a smooth color change observed. This soft color pattern tells us that tanks larger than 1500 gallons have no significant effect on IR (Figures 15, 16, and 17).

3.4.2 Irrigation Replacement of Plants (Tomatoes, Cucumbers, and Beets)

The difference in irrigation replacement rates continues to increase slightly between the 1500-gallon tank and the 3000-gallon tank. Depending on the type of plant selected and tank size, the states with the lowest IR (%) over the same tank size range ranged from CO; 16%-25%, CA; 11%-28%, TX; 32%-59%, and SD; 36%-64%. Again, within this range of tank sizes, VT has the highest IR of 90% for all three plants (Figures 12, 13 and 14).

3.4.3 Tank size and potable water irrigation vs Irrigation needs met from RWH.

As tank size increases, the amount of potable water used for irrigation decreases. However, while this decreasing trend is significant in some states, it is relatively less in other states such as CA and CO. Based on the results, it is clear that the amount of water used from the tank for irrigation is directly related to both the rainfall received during the growing season of the crop and the total regional rainfall. In Vermont, using 2500 and 3000-

gallon tanks, it was calculated that more than 98% of the plant's water needs could be met with stored rainwater.

The amount of potable water used for irrigation is also inversely proportional and directly related to the irrigation demand met by the RWH. This is because potable water is assumed to be used when the amount of water in the RWH tank is insufficient for irrigation. For example, the percentages of minimum and maximum total irrigation demand met by the RWH tank are highest for tomato irrigation, approximately 39-100%, and 21-81% for VT and AR, respectively. The main reason for the highest percentage of irrigation demand met by rainwater harvesting in Vermont is revealed by the analysis of 31 years of rainfall data, which is probably due to the region's abundant rainfall during the crop growth period. The opposite is true at least for CA and CO with 3-17% and 5-21% respectively (Table 5).

In California and Colorado, on the other hand, this proportion is much lower due to the relatively limited rainfall during the growing season and the general lack of rainfall in the region (Figure 18 and Table 5). Overall, in almost all states, a rapid increase in the percentage of irrigation covered by RWH was observed for tank sizes between 250 and 1000 gallons, while this trend slowed for tank sizes of 1500 gallons and above (Figure 18). This trend is further supported by the IR assessment graphs (Figures 12, 13, 14, 15, 16, and 17).

3.4.4 RR (Runoff reduction)

Studies have shown reductions in overflow through Rainwater Harvesting (RWH), as indicated by studies conducted by (Endreny & Collins, 2009; Shuster et al., 2008; Young et al., 2009).

While roof runoff after rainfall is stored in the tank, the excess continues to flow beyond the tank's capacity. Here the RR value goes to 0% when the tank starts to overflow. As the tank size and the amount of water used from the tank increases, in other words, as the tank overflow time is delayed, the RR value is 100%. This phenomenon, when analyzed using calculated overflow data corresponding to different conditions, has a positive impact on runoff reduction in states with low rainfall and high ETo values. Small runoff reductions were observed in AR, GA, IL, KY, MI, MO, VT, and WA which are all states with relatively high precipitation. In high-precipitation states, such as Washington, average annual runoff reductions of less than 1% were calculated (Figure 21). In the states of CA, CO, SD, and TX, runoff reductions between 30 and 80% are observed. However, as shown in Figure 21, it is possible to say that there is a direct relationship between the increase in tank size and the reduction in runoff for each state. However, the average overflow, shown by the orange line, is not affected by tank size (Figure 21).

A study in the Portland, Oregon area found a 68% reduction in flow with a 4500-gallon residential tank (Crowley, 2005.). Another study found a reduction in peak flow of less than 10% for a single-family home (Gilroy & McCuen, 2009). The results suggested that the Rainwater Harvesting (RWH) tank can reduce the peak intensity of rainfall in various storm events, depending on factors such as the capacity of the tank and the characteristics of the rainfall, as observed in the study by (Ibrahim et al., 2019).

In general, the highest RR (%) values were calculated for tomato crops with a wide range of growing seasons for all states. This result shows that the more RWH is used for irrigation, i.e. the more stored water is used, the more positive the effect on RR is. It is important to note that in this study, the RWH technique was specifically designed to be used only during the growing season of the crop, and this was considered when calculating the corresponding values.

The Stormwater Management Model (SWMM) developed by the Environmental Protection Agency (EPA) has been used to replicate the impacts of water supply and runoff reduction at a watershed level, as discussed by (Steffen et al., 2013; Walsh et al., 2014).

3.4.5 Average Flow Reduction and Overflow Relationship by Tank Size

When analyzing overflow data for tanks with a capacity of 250-3000 gallons in selected states, none of the tanks of this size were found to be able to completely prevent overflow during the growing season of cultivated plants, (Figure 21). There exists a strong, inverse relationship between overflow and runoff reduction. Storing a larger volume of rainwater is the only way to completely prevent overflow, but this has a negative impact in terms of operating costs.

3.4.6 The Correlation Matrix between Evapotranspiration Depth, Runoff Reduction, Irrigation Replacement, Tank Sizes, and Precipitation

Varying tank sizes consistently reduced runoff by 10% across all three crops. This value reflects the average runoff reduction value of all tank sizes (Figures 25, 26, and 27). If we analyze the correlation between the parameters in our RWH model and the data obtained from these figures, the results indicate the following.

A negative correlation between precipitation and runoff reduction was observed: tomato -80%, cucumber -78%, and beet -69%. Furthermore, the reduction in runoff was positively correlated with ET Depth with values of 59%, 58%, and 50% for tomato, cucumber, and beetroot, respectively. On the other hand, a negative correlation existed between alterations to irrigation and decreases in runoff, with percentages ranging from 54% to 46%.

Specifically, there is a direct correlation between changes in irrigation replacement and precipitation. Cucumbers had the lowest correlation at 43%, while beets had the highest at 47%. When we look at irrigation change and tank size, we see a direct relationship between 57% and 53%. In all three crops, there is an inverse relationship between irrigation change and ET Depth around 60%.

3.4.7 Relationship between irrigation replacement, runoff reduction and Precipitation/Evapotranspiration of crop

In general, as the tank size increases, the P/ET value at which the IR value reaches 100% decreases. For a 1000-gallon tank, the IR reaches 100% with a P/ET of around 3, while for a 2500-gallon tank the P/ET at which the IR reaches 100% is just under 2. However, in the 250- and 500-gallon tanks the IR reaches at most about 50% and 75% respectively (Figure 28). As can be seen in Figure 29, there is no significant interaction between tank size and P/ET. The RR vs P/ET pattern distributions are almost similar for each tank size. However, for tanks of 1500-3000 gallons the RR for tomato plants can reach 100%, while for tank sizes of 1000 gallons and below the RR does not reach 100%.

Both scatter plots show that the P/ET value reaches 100% for RR and IR at lower values for the 1500–3000-gallon tank size. Here, when the P/ET value is above 2, the RR value starts to hover around 25%. After this value, overflow starts to occur for each tank size and the RR value stabilizes (Figure 29). These results suggest that, in general, a 1500-gallon tank has an optimal effect on RR and IR in the selected states.

3.4.8 Irrigation cost calculation annually

Here, the irrigation cost savings from RWH are calculated as follows.

3.4.8.1 Potable water irrigation cost (gal/year)

In this study, to compare the effect of RWH on irrigation cost, the cost of irrigation of three crops (Tomato, Cucumber, and Beets) was calculated if the irrigation was done primarily with potable water. According to our results, the highest cost belongs to KY with $545. The lowest cost belongs to AR with $241 (Figure 31).

3.4.8.2 The actual amount of money saved for irrigation for three plants.

We computed the potential cost savings for irrigation using RWH water. For tomato irrigation, Kentucky showed the greatest savings at approximately $510, followed by Vermont at approximately $506. California and Colorado had savings of less than $60 for all three crops (Figure 32).

3.4.8.3 Money saved on irrigation by RWH, including annual tank costs.

Overall, our analysis shows that savings decrease as the tank size increases after a certain point. Furthermore, the tomato plant, which exhibits the highest annual growth rate, results in the highest amount of savings. Using a 3,000-gallon tank for irrigation was observed to save money when growing tomatoes in only a limited number of selected states. The states with savings for this tank size are GA, KY, MO, VT, and WA, with savings of approximately $57, $158, $11, $154, and $4.5, respectively (Figures 33, and 35). It is noteworthy that the states with the lowest savings are CA and CO, which show negative values for each tank size and each of the three selected crop irrigations. For the lowest selected tank size of 250 gallons, CA, and CO yield losses of roughly -$21 and -$10, respectively. The results show a loss of approximately $304 and $265 in the respective states for a 3000-gallon tank. The states of VT and KY show significant savings for the same tank sizes and for all three crop irrigations. In addition, for each of the three crop irrigation systems in these states, there are potential savings from irrigation up to 1500-gallon and 1000-gallon tanks. (Figures 33 and 35). States with irrigation savings for all three crops and tank sizes varying by state include AR, GA, IL, KY, MI, MO, VT, and WA.

States/Tank Sizes	250	500	1000	1500	2000	2500	3000
AR	✓ T, C, B	✓ T, C, B	✓ T	-	-	-	-
CA	-	-	-	-	-	-	-
CO	-	-	-	-	-	-	-
GA	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T
IL	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T	-	-	-
KY	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B
MI	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T	-
MO	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, B	✓ T
SD	✓ T, C, B	-	-	-	-	-	-
TX	✓ T, C, B	✓ T, C, B	-	-	-	-	-
VT	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B
WA	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, C, B	✓ T, B	✓ T, B

Table (7) Tank sizes saved by plant species selected from RWH irrigation. Tank sizes saved by plant species selected from RWH irrigation. *T: tank dimensions that saved money when only tomatoes are grown. *C: tank dimensions that saved money when only cucumber are grown. B: tank dimensions that saved money when only beets are grown.

The states that demonstrate money savings with the RWH system based on the tank sizes and crops grown are SD tank up to 250 gallons; TX tanks up to 500 gallons; AR tanks up to 500 gallons; IL tanks up to 1500 gallons; MI tanks up to 1000 gallons, while GA, KY, MO, VT, and WA allow tanks up to 3000 gallons, the largest tank size selected in this study. However, in CA and CO, even using the smallest tank size of 250 gallons does not save money (Table 7). On average, these two states incur annual costs ranging from 10 to 20 dollars. The state with the least savings, SD, saves about \$2.5-\$7 per year with a tank size of 250 gallons. The state with the second lowest savings is TX, with a savings of around \$10 (Figures 33, 34 and 35).

Modeling exercises have revealed that tanks when installed, may exceed the necessary capacity relative to demand (Ward et al., 2010). Therefore, to enhance cost-effectiveness throughout the system's lifespan, it is crucial to accurately determine the system size. This is essential to mitigate expenses linked to oversized tanks and prevent a rise in the water age (time interval when the water is waiting in the tank (Wales, 2006).

3.5 Conclusion

Research findings highlight the relationship between irrigation substitution and precipitation patterns. This project provides an in-depth analysis of rainwater harvesting's contribution to reducing rainfall-induced runoff, as well as its ability to meet irrigation water needs for crop cultivation and reduce reliance on potable water resources. It may also be an exemplary study to contribute to a comprehensive assessment of the economic implications and potential impact on additional water resources in water-scarce areas.

Based on the calculations and the correlation between tank sizes and irrigation replacement, we predict a linear relationship between 53% and 57% (Figures 25 and 27). Overall, we observe that the increase in irrigation replacement values decreases in all states after reaching the 1500-gallon tank size. There is an inverse relationship between rainfall and runoff reduction (RR) achieved by rainwater harvesting (RWH). Moreover, this ratio increases in magnitude with a negative correlation as the growing period of the plant increases. Given the influence of tank size on irrigation replacement (IR), it is reasonable to assume that the occurrence of rainy periods during the crop-growing interval directly affects the results. In some states, only irrigation from tanks was able to fully cover crop water requirements, as rainy days aligned with the growing season over time. In some years, however, it was observed that the use of potable water for irrigation increased due to insufficient rainfall.

For tank sizes up to 1500 gallons, there is no marginal difference in runoff reduction (Figures 25, 26, and 27). Colorado and South Dakota with the lowest rainfall and Texas with the highest ET_o show a slight increase in runoff reduction as tank size increases (Figure 10).

The amount of rainwater supplied for irrigation and the parameters RR and IR are influenced by several factors, including annual rainfall, rainfall during the growing season, tank size, and the ET_c of the crops planned to be planted. For RR, among the selected states CO, and SD have the lowest annual rainfall, CA receives only 11% of the annual rainfall during the growing season, and TX, which has the highest ET_c, has higher RR (%) compared to other states (Figure 21).

For IR: due to all these parameters and conditions mentioned above, no tank size can reach 100% IR in the same states. For the other states the IR is more than 90% for almost all of them. Only WA reached a maximum of 84% for the 3000-gallon tank (Figures 12, 13, and 14). In summary, it can be said that the less rainfall the region receives during the growing season, the larger the tank size used for rainwater and the higher the ET_c value of the plant has a positive effect on RR (%) and a negative effect on IR (%).

When the cost-effectiveness of the study is evaluated, it is revealed that the use of the RWH technique in tomato cultivation, which has the longest growing period among the selected crops, saves more money in more states than the other two crops. The amount of money saved for tomato cultivation increases in some states depending on the size of the tank used. As the tank size continues to increase, the amount of money saved in these states increases up to a certain tank size and then tends to decrease, leading to cost losses in some states as the tank size continues to increase.

The key factors for achieving an effective Rainwater Harvesting (RWH) system in high tunnels are determining the amount of water storage and the optimal tank size that saves money. While the value of irrigation needs met by rainwater harvesting increases rapidly up to a 1500-gallon tank capacity and continues to increase at a slower rate for larger tank sizes, based on the amount of money saved from a rainwater harvesting system, it cannot be concluded that a 1500-gallon tank size is ideal for all selected states (Figure 32.) The amount of money saved through rainwater harvesting (RWH) in a region depends on several factors, including local tap water prices, rainfall during the growing season, and the amount of harvested rainwater stored for irrigation. These parameters have a direct impact on the total amount saved from RWH. Although no rainwater harvesting (RWH) is saved in California and Colorado, these two states have achieved the highest runoff reduction percentages (RR%). This study shows that the RWH system can be advantageous for all regions, not only in terms of cost savings but also in terms of more efficient use of our natural water resources (Scholze et al., n.d.; Sepehri et al., 2018).

CHAPTER 4: Conclusions and suggestions

The positive effects of rainwater harvesting techniques on both the conservation of existing water resources and stormwater management have been demonstrated by many studies and references given in Chapter 2. This study analyzes the cost-effectiveness and runoff reduction of the RWH technique for plant cultivation using high tunnel roof.

To summarize the results obtained, the water needs of plants depend on the ET_o values of the region and K_c of values of the plant. The efficiency of meeting this water requirement from RWH and IR values are generally directly proportional to the rainfall rate of the region during the growing period of the plants and the tank sizes used. As for the RR values, it was observed that the less rainfall the region receives, the higher the RR (%) value obtained through RWH. For RR it can be said that increasing the tank size and using the accumulated rainwater in the tank during the rainy season are the most important positive factors. Increasing the use of the water accumulated in the tank to achieve an effective runoff reduction rate can almost eliminate the effect of tank size on this. Because each time the tank is emptied, new space will be created for the rainwater generated by the rainfall.

For cost-effectiveness, increasing tank size increases costs. Besides this, the amount of municipal water cost of the region is the most important parameter for the cost. The higher the municipal water cost, the more money is saved through RWH. On the other hand, cost-effectiveness depends on the amount of rainfall the region receives and the water requirements of the plants. As the amount of water used from the tank increases, the amount of money saved also increases.

This study does not consider the water storage that may occur on the high tunnel roof as a result of snowmelt. In addition, ET_o data is not specifically determined for the high tunnel when calculating ET_c. In the closed environment provided by the high tunnel, there may be more evapotranspiration than outside due to the increase in temperature, especially in the middle of the summer months. In future studies, a specific ET_c for the high tunnel can be determined according to plant species. In this way, more accurate plant water requirements can be determined.

A larger roof area could be used for future work. More rainwater can be collected from the larger roof area. For example, in this study only the high tunnel roof was used, in addition, if available, the roofs of all suitable structures on the farmland can be used for RWH. In addition, if the land around the high tunnel is suitable, the surface can be shaped and the runoff after rainfall and the overflow from the roof can be directed to a well that may exist on the land for ground water supplement.

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