DESIGN AND DEVELOPMENT OF AN INTEGRATED WATER SYSTEM COMBINING RAINWATER HARVESTING SYSTEM (RHS) AND ATMOSPHERIC WATER GENERATOR (AWG)

by

Fatema Tuz Zohra, B.Sc.

A thesis submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Master of Science
with a Major in Engineering
August 2020

Committee Members:

Bahram Asiabanpour, Chair

Heping Chen

Namwon Kim

DEDICATION

To my mother Anowara Begum, the reason what I become today. Sadly, she died in 2016, leaving an unfathomable void in my heart. But I always remember the lessons she taught me for perseverance and self-confidence.

ACKNOWLEDGEMENTS

First and foremost, praises to the Almighty, for keeping me strong and motivated through my research work to complete it successfully.

I would like to convey my sincere gratitude to my thesis supervisor, Dr. B. Asiabanpour, for allowing me to work for my thesis under his supervision. His vision and enthusiasm for research work have highly encouraged me. Not only he has taught me how to carry out this research process and to present my work, but also, he has supported me with his patience during my hard times of adjusting myself in American study culture. It has been a great privilege to work and study under his supervision, and I am equally excited to work with him again in my doctoral study.

I am extremely grateful to my classmate Otto Randolph, Jr. and his parents Mr. and Mrs. Randolph, for their love, prayers, and support throughout my study and especially for extending a kind hand for protecting my little daughter in the challenging times.

I am very much thankful to my 3-year-old daughter, Mazneen Akanda Maya who has been very understanding of her mom's work and sacrificed her quality time with me so that I can finish my thesis on time. My husband, Md. Muzaffer Hosen Akanda with his 10-year long expertise in the power generation field has helped me with important directions and instructions to establish the experimental setup and recording my work. I am forever in debt for their tolerance, affection, and assistance during this whole journey of my master's study.

My special thanks also go to Isaac Olson, Automation Undergraduate Researcher, and my friends Md. Rezwan Matin & Md. Rafiqul Islam, graduate students at Texas State University for providing me important advice and direction related to my thesis work.

I am extremely grateful to two of my teammates McKeever P Starnes and Alexander J Little, undergraduate research assistants for providing me extensive support related to automation and water quality analysis in this project.

Last but not the least, I am extending my thanks to the Freeman Center, and Ingram School of Engineering at Texas State University and to the US Department of Agriculture (grant number 2016-38422-25540) providing funding and access to infrastructure and laboratory support. Sponsors are not responsible for the content and accuracy of this article.

Finally, my heartfelt thanks go to all the individuals who have supported me through this process of completing my research work successfully.

Fatema Tuz Zohra

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

Figure **Page**

ABSTRACT

The *objective* of this research is to design and develop a smart integrated water system that combines two off-grid freshwater resources- Rain Harvesting System (RHS) and Atmospheric Water Generator (AWG) to establish a potential solution to the *problem* of freshwater scarcity. A preliminary study and data analysis are carried out based on the local (San Marcos, TX) historical precipitation and atmospheric water generation data to figure out the suitability of the idea to integrate these two off-grid (independent from municipality water grid) water systems. A vertical farming unit in the Freeman Center, San Marcos, TX, is considered as a case study to implement and test this water system, and smart automation is introduced to meet the fitness of this farming unit. Later, water quality is tested to evaluate the fitness of this water to aid plant growth and good health. Finally, a suitable water storage tank capacity is determined for this integrated system based on the water demand pattern of two soilless farming units. This article explains the procedure, component modification, and construction strategy for data analysis, mechanical and electrical systems, network, and data logic design for the implementation of this integrated system. An experimental setup is established in the lab to test if the smart logic system for automation is working correctly with all the electrical components. Given the COVID-19 pandemic situation, fabrication/installation of related electrical and mechanical equipment onsite is not possible.

Results of the data analysis showed that RHS-AWG integrated system could provide stable and sustainable water. Introducing smart automation through real-time

feedback from surrounding atmospheric conditions and automatic refill of nutrition supply tanks facilitates energy-saving and eliminates labor in this project. The water quality of this system resembles the purest water with an acceptable pH range and a combination of minimum salinity and minerals suitable for nutrition control for the growing plants. Based on the local (San Marcos, TX) rainfall data, it is found that RHS alone is enough to meet the required year-round water demand with a bigger storage tank capacity. Still, having AWG as a back-up in this integrated system ensures the availability and supply consistency for the months when there is almost no rainfall. This research is vital because integrating more than one off-grid water system with vertical farming units can be an all-in-one potential solution of the uprising freshwater and food scarcity problem. In remote areas, this can reduce the dependency on municipality water or other freshwater resources such as a river, wells, and underground water. Although this water system is specifically designed for a vertical farming unit, it is scalable and adjustable for any freshwater-related application. An integrated RHS-AWG-Municipal water system can be investigated to optimize cost and risk to make this system more applicable for public use. Radiofrequency and wireless technologies, cloud data collection, etc. can be used in the future for analyzing weather-related forecasting data to offer more compliant design of the water system.

1 INTRODUCTION

With the growing population in the world, the developing countries are facing insecurity with growing food and supplying freshwater to meet the demand [1]. Almost 1.2 billion people in the world do not even have access to safe water [1][2]. Figure 1 below shows how much the water withdrawal percentage has increased around the world in color coding from 1995 and a prediction for 2025 [3]. Notice the span of orange and yellow colored regions increased significantly over time.

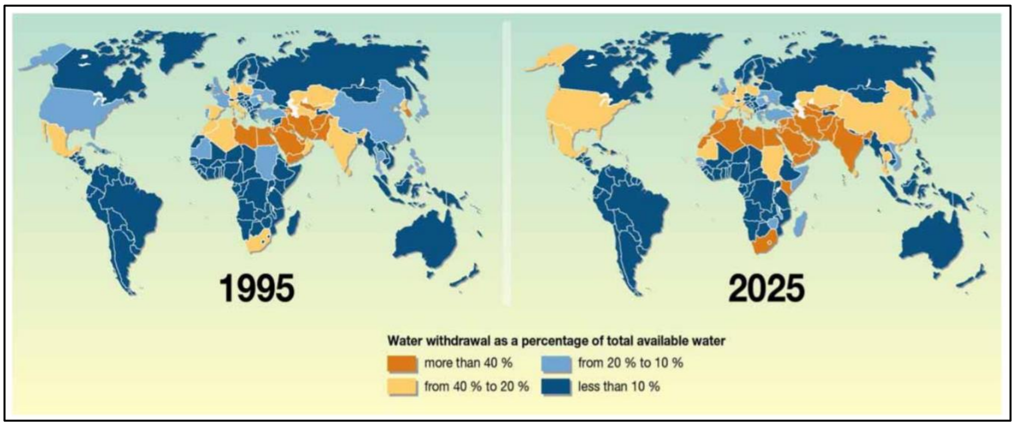

Figure 1: Water withdrawal percentage of total available water [3].

Figure 2 shows that agriculture is considered the highest consumer of the world's freshwater, about 70% [4] [5]. 40% of the world's population faces water scarcity at least for a month each year [6]. The planet has to prepare to feed around 9 billion people by 2050, which requires an anticipated 50% increase in cultivated production along with a 15% increase in freshwater withdrawals [4].

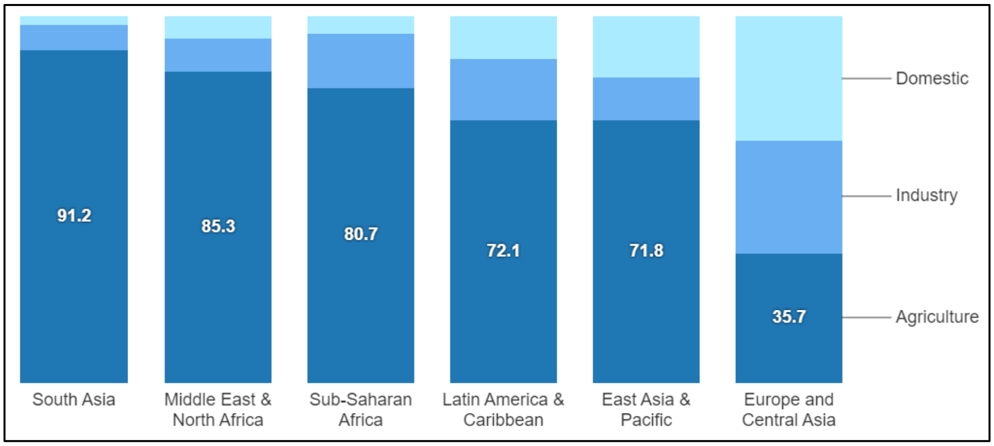

Figure 2: Consumption of freshwater by percentage around the world [4].

With modern vertical farming systems such as hydroponics, higher yield is possible with much less water and fertilizer than conventional farming [7][8] and is considered a viable approach. In such soilless agriculture, plants are grown inside a controlled environment where plant roots are submerged into nutrition solutions and placed in vertical racks to utilize space (Figure 3).

Figure 3: Hydroponic farming [9], Vertical farming [10].

The benefits of this farming method are- almost no weeds, no pests, double growth rate, nutrition efficiency, and only 20% of water usage compared to conventional farming.

However, this system performs better with the use of pure water as it provides control over the pH level, which can facilitate maximum nutrition absorption by the plants and good yield [11]. Additionally, designing vertical farming in the form of off-grid enables the possibility to move such a system anywhere in the world without any restrictions regarding access to utilities. The municipality supply water is usually treated with disinfects (Chlorine, Chloramine, etc.) to kill germs. Aluminum sulfate is used to coagulate impurities, sand filters for filtration, and add lime to adjust pH levels, resulting in their by-products, inorganic and organic chemicals, radionuclides [12][13]. Hence the supply water is not the best source of water for vertical farming.

The 'Evergreen' project at Freeman Ranch [14] is considered as the application site for this smart integrated water system to analyze its performance. There are two shipping containers, and one is being used for vertical farming already to its full capacity. This unit consists of 8 vertical sets of columns where different types of plants (Lettuce, Spinach, Basil) are growing. Individual 50-gallon capacity supply tanks are positioned under each rack to supply nutrition-mixed water to the respective racks. This unit can be replicated for the other shipping container. Hence, during water demand related calculations, the total number of supply tanks is considered 16 for the two units of vertical systems.

Local surface and underground freshwater are limited and declining in places in the world. Rainwater harvesting has been used as a common practice to collect and use water for many years [15]. Figure 4 (a) shows a typical rainwater harvesting system with all its components. Although rainwater is free of cost, it is inconsistent, unpredictable, and sometimes in-sufficient for many parts of the world. Therefore, a supplementary source of water is necessary.

Atmospheric water generation is comparatively a new method that captures water from the moisture in the air. It cools down the air and condensate the vapor that is present in that air, collects it and passes through a set of filters to eliminate any pollutes as shown in Figure 4 (b). However, this method is usually energy intensive and performs only in certain ambient conditions [16].

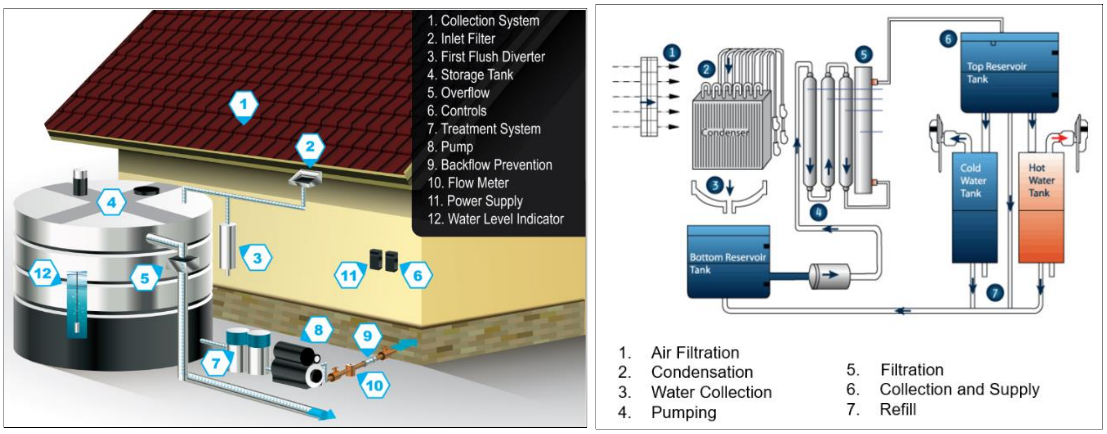

Figure 4: (a) Components of a Rain Harvesting System [17] and (b) Structure of a condensation-based AWG system [18]

Researchers have proposed a new term- 'Moisture Harvesting Index (MHI)' to assess AWG's feasibility in any specific area. They defined MHI as "the ratio of the energy invested in the desired water condensation process to the total energy invested in the cooling of the condensable as well as incondensable gasses in the air bulk".A global assessment of feasibility done based on this MHI index considering MHI>0.3 as a suitable time in the same study is shown below in Figure 5:

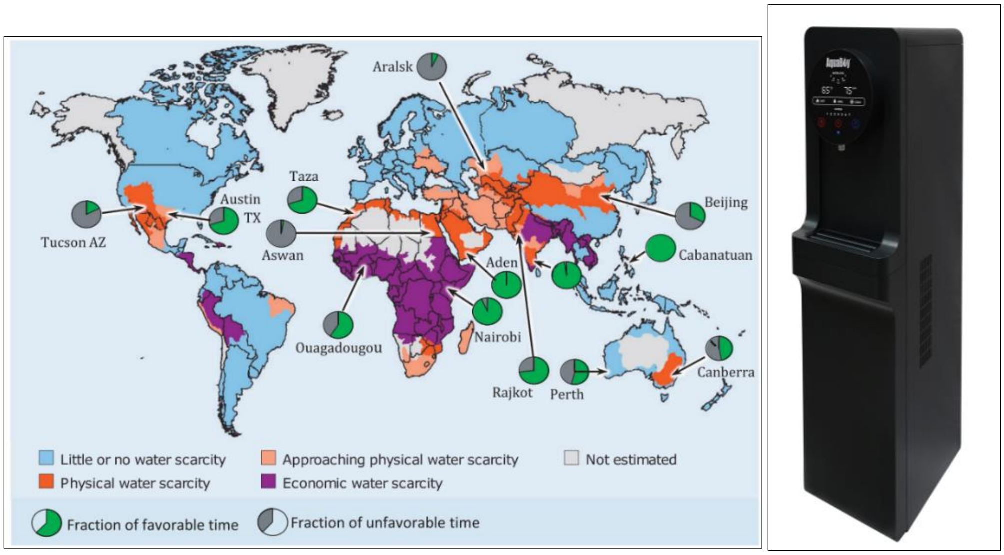

Figure 5: Fraction of favorable time for AWG operation based on meteorological data (2005-2014) combined with physical and economic global water scarcity map [19]; AWG on the right.

They found that, except for extreme weather areas, the coastal areas show the highest AWG production feasibility with higher humidity and warm climatic conditions even if it is in arid regions. For example, in Yemen (severe water-scarce country), coastal cities Aden and Hodeida have about 99% of the favorable time for AWG operation [19]. Our preliminary observations also align with this study as we collected data for AWG production for four years (2014-2017) for the San Marcos area- a city adjacent to Austin, US. Combining the precipitation data for the same years, it is found that rainfall and atmospheric water generation systems peak in their water production in opposite seasons several times during a year. Such observation has led us to investigate its accuracy and then to pursue an integrated system where these two freshwater sources are utilized to supply consistent, pure water for drinking and farming purposes.

1.1 Purpose of Research

While designing and developing a smartly automated integrated system, few questions come in mind. How can better this integrated system performance compare to a single water system in terms of technical benefit? How smart automation to this integrated system can be introduced, and what benefit it has? What is the difference in water quality and compatibility between this integrated system with a conventional supply water system? And finally, can this design be flexible enough to implement according to demand and application type?

This research intends to propose an innovative method to combine Rainwater Harvesting System (RHS) and Atmospheric Water Generator (AWG) together as one which can make the water system more consistent, economical, independent, and automated. This investigation requires the following set of hypotheses to be assessed and confirmed.

Hypothesis 1: *Based on the historic precipitation in the San Marcos area and performance of the AWG systems, an integrated system of AWG (always ON status) and rainwater, brings more consistency to the water production.*

Hypothesis 2: *Addition of Smart AWG (ON only when rainfall for the month is below long-term average) to RHS brings more stability to water production than always ON AWG to RHS.*

Hypothesis 3: *The integrated system (RHS and AWG together) can automatically collect, store, filter, deliver, and supply water to the point of use.*

Hypothesis 4: *This automated system can perform as a superior watering mechanism in terms of water quality and integrate-ability for the automated vertical farming system.*

Hypothesis 5: *For every location and demand, an optimum RHS and AWG system size and capacity can be calculated.*

1.2 Impact of Research

Food and water are the basic needs of our growing population, which are very difficult to fulfill daily due to our lifestyle changes, scarcity of land, and limited freshwater sources. This integrated system can play an active role in meeting this demand in the form of a source for the vertical farming system. However, its application is not only limited to vertical farming. Instead, this system can work as an independent water source for household and industrial use as an effective alternative to the big city-water-supply facility and any deserted area of the world.

1.3 Literature Review

This section describes about the past study that are done related to the scopes of this research in following sections.

1.3.1 *Rainwater Harvesting System (RHS)*

Rainwater harvesting has been used for many years for irrigation and other non-potable use [20]. Office scale systems have been studied to use the rainwater for water closets to compare with the amount of main supply water that can be saved. 87% main supply water was saved during 8-months of the period, and the energy cost that is associated with the pumping was negligible compared to the water bill from supply water [21]. Also, small scale and large-scale rain harvesting systems were considered for assessing over 29 years of rain data in Malaysia. It is found that the reliability of this system is 93%-100% [22]. Highly populated states in the United States were taken into consideration to assess the demand for outdoor water usage such as gardening, car wash, washing clothes, etc. vs supply of water that can be collected from rooftops. Except for arid regions, it was found that it is possible to meet 100% of this ***non-potable*** demand (even for Arizona, Texas, etc.) only by collecting rainwater from the roof-space [23]. Historical data (Figure 6) shows an increase in rainfall over the years from 1986 to 2016; the scale is 0 cm (green) to ≥ 200 cm (red) of precipitation in Texas [24].

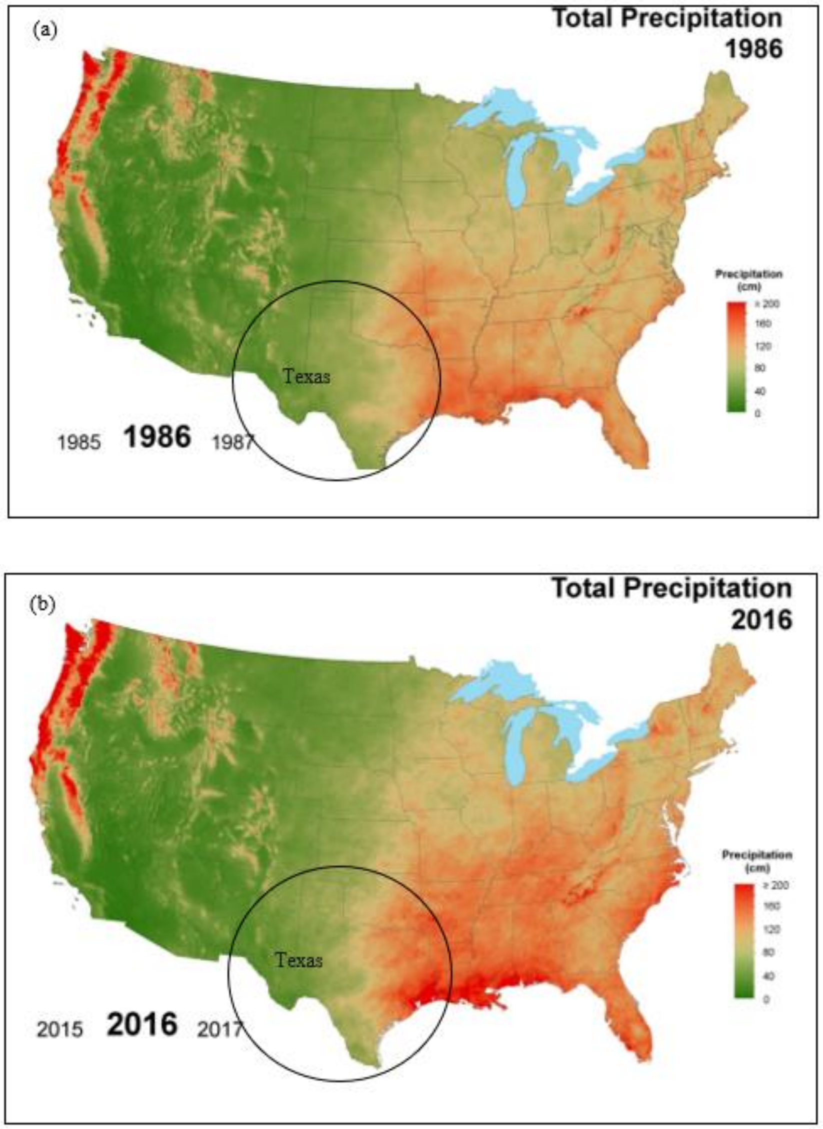

Figure 6: Total precipitation comparison based on historical data (a) year 1986 vs (b) year 2016 in United States [24].

However, specific design criteria are recommended while designing the Rain Harvesting System. This system's design parameters are usually precipitation data of a particular area, catchment area, collection efficiency, storage tank volume, and demand for water. Operational parameters are rainwater use efficiency, water-saving efficiency, and number of cycles. The ratio of water tank volume to catchment area i.e. how much water can be collected for certain roof area is calculated based on water demand, rainfall data, and available resources. A Decision Support System (DSS) was also developed to determine the tank volume for any specific site by analyzing appropriate data. This system was validated for 9 case studies conducted in the state of Mexico [25]. Since this technology is easy to install commercially, a local service team experienced in design and installation was chosen to install the RHS in the 'Evergreen' site (Freeman Center) [14].

1.3.2 *Atmospheric Water Generation (AWG)*

As for the regions, where rain is insufficient to meet either or both potable and non-potable demands, such as Texas (insufficient to meet both kind of demands) [23], alternative independent source such as atmospheric water generator (AWG) system can be introduced as a complementary source. The idea of atmospheric water generation came from biomimicry (Figure 7).

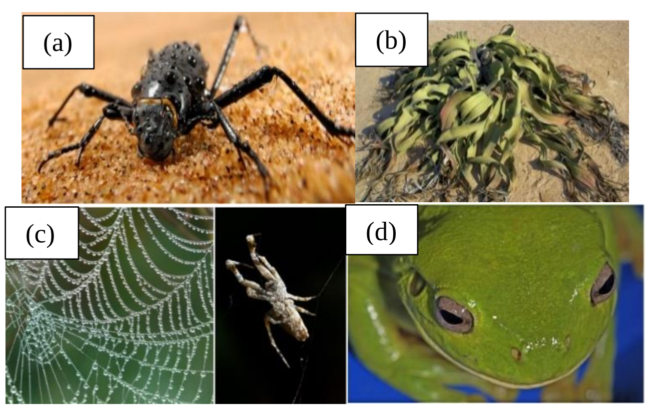

Figure 7: Biomimicry examples: (a) *Stenocara gracilipes* (beetle) [28]; (b) *Welwitschia mirabilis* (plant)[29]; (c) *Uloborus walckenaerius* (spider) with its web [30]; (d) *Litoria caerulea* (frog) [31].

There are some beetles (*Onymacris bicolor, Onymacris laeviceps*, *Stenocara gracilipes*,), plants (*Welwitschia mirabilis*, *Discocactus horstii*), grass and animals (*Litoria* *caerulea, Moloch horridus, Uloborus walckenaerius*) in nature who are capable of capturing the moisture from air and use it for survival [26] [27]. Most of them are species that grows and lives in the desert climate.

There is always some moisture content present in the atmospheric air, and extraction of this moisture can be done in many ways (Figure 8), such as- cooling the surface, desiccation, and separating membranes [32]. Cooling of the surface is the most popular way to collect moisture, and it can be done with or without the help of refrigerant, but it usually requires a lot of energy to operate the systems. Also, refrigerants are not usually environment-friendly substances. Another way is to use desiccates, which has an affinity for moisture and absorbs it. Heating these sorbents would release the moisture, which can be cooled and collected. Again, this process includes heating and cooling and, finally, energy consumption. Separating membrane technology is using polymers that selectively allow water vapor to go through the membrane except a gas/vapor mixture. Although this process reduces energy usage, it still has some challenges, such as membrane fouling, a variation of vapor partial pressure [32], etc.

At present, AWG products are available in the market, which uses the refrigeration system, and the devices look like typical water dispensing machines. These devices cool down the air passing through its air filter and condensate the moisture that is present in the air and collect it. Then the collected water is run through a set of filters to ensure that it is disinfected and safe to drink. However, as the production depends on the atmospheric condition, a prediction curve (Figure 9) has been developed to estimate the amount of water production at different combinations of temperature and relative humidity [16].

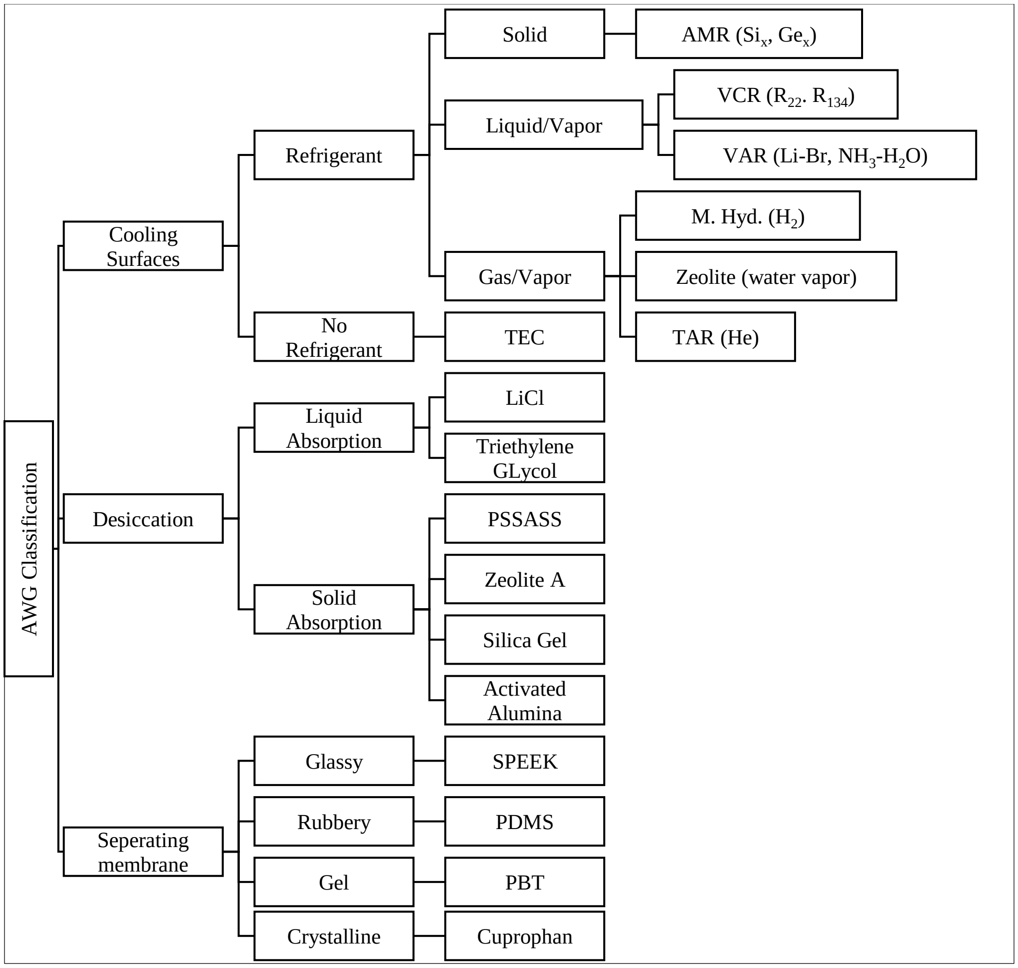

Figure 8: Classification of AWG technology. Data source [32]

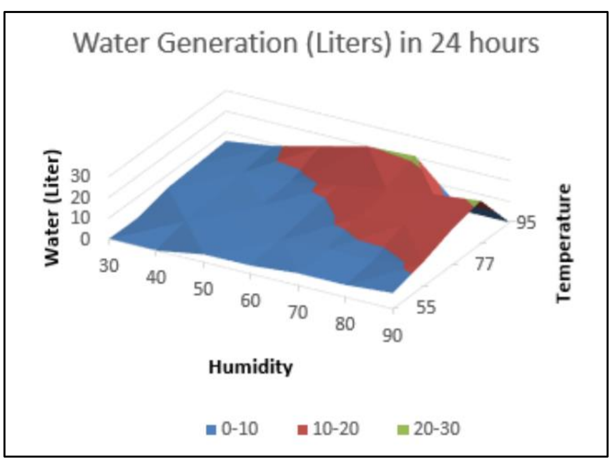

Figure 9: Prediction curve of average water generation for given relative humidity in % and atmospheric temperature in Fahrenheit [16].

As mentioned earlier, warm and humid areas are suitable for getting the highest possible water production from AWG [19]. Even though the production comes at the cost of energy, it can be considered a better alternative to a traditional chilling machine and bottled water when it is operated by renewable energy such as solar or wind turbines [33].

1.3.3 *RHS and AWG- Integrated Systems*

Only a few cases have been found in recent studies where rainwater system has been integrated with other water sources such as the centralized water supply [34][35]. Still, so far, no study was found to integrate AWG with other water systems. Integration of independent natural water sources such as fog, dew, and rain alone can be a good source of freshwater depending on the semi-arid coastal areas free from industrial pollution with light sterilization at comparatively low cost [36]. It is found that integration with centralized water source can complement (in case of potable water supply) or reduce centralized water use (in case of non-potable use) and decrease associated costs dramatically when renewable energy is used to run the system. As rainwater and atmospheric water both are free but not consistent and dependent on atmospheric conditions, integration of RHS with AWG can lead to a potentially consistent water supply system. A preliminary study has shown that there is a possible relation between both systems reaching their peak production in opposite seasons.

1.3.4 *Automation*

Smart automation of a water system indicates that the system will perform automatically and will take the decision to turn on or off its sub-systems, taking input form real-time feedback or analyzing previous data. So far, many technologies have been developed for automation of different water facilities, water treatment plants, and even for the storage tank and water pumps. Raspberry pi [37] [38], Arduino [39] [40], a simple algorithm for water pump [41], smart metering [42], supervisory control and data acquisition (SCADA) system, remote sensing with underground sensors and alarm system [43] are some recent technologies that are being implemented worldwide. Apart from these, many commercially available sensors (Figure 10) such as DUV 2/0,005-5 (Kazakhstan), INNOLevelECHOIL-EC-A (Russia) and Siemens Sitrans Probe LU (Germany) are used (Figure 10) for recording the water level by measuring the distance between the sensor and surface water surface [44] [45].

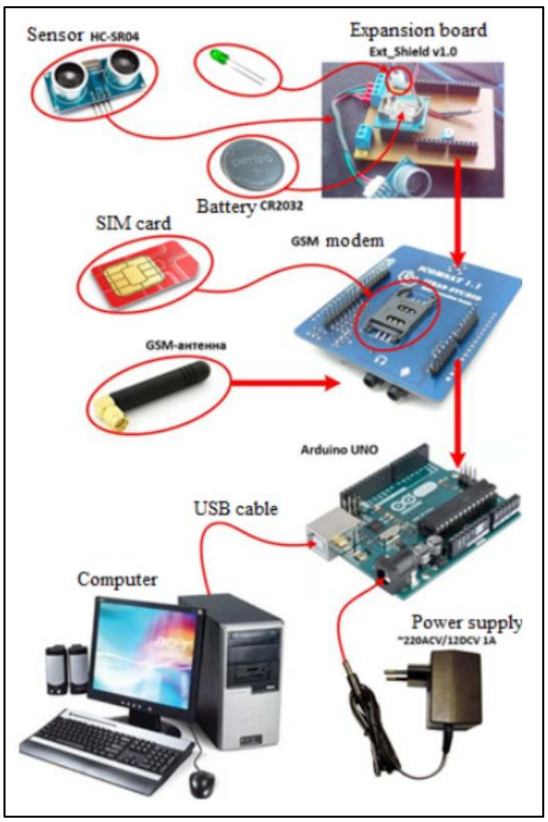

Figure 10: Connection diagram of the sensor DUV 2/0,005-10 and a computer [45]

With the aid of Raspberry Pi or a typical computer and Python software, Arduino microcontrollers can be reprogrammed and modified for a program-based control system which is effective and cost-efficient [45]. A combination of the sensors and control systems can be feasible for the successful automation of the proposed integrated system.

1.3.5 *Water Quality*

For hydroponic farming like vertical ones, the quality of water is essential. Since many kinds of nutrients are necessary for different types of growing plants, pure water makes it easy to control the amount of nutrients in the water. According to the book "Hydroponics- A standard Methodology for Plant Biological Researches" edited by Toshiki Asao (2012) suggests that there are three most important metrics to consider while determining water quality or nutrient solution for hydroponics- 1. pH level, 2. electrical conductivity and 3. the composition of anions and cations [46].

The pH level: This indicates how acidic (0 to <7) or alkaline (>7 to 14) the water is on a scale of 0 to 14 and 7 being neutral. The book edited by Toshiki Asao suggests that it is essential that the nutrients are in the chemical forms and in ions to be able to be absorbed by the plants from water. It has been observed that NH_3 can be present as NH_4^+ at a pH range of 2-7 but decreases in concentration as the pH increases to higher values. Even at pH 8.5, the NO_2^- decreases to a level that is harmful to the plants because it reduces the plant's nutrient intake capability. Therefore, a pH level is recommended to be between 5.5 – 6.5 to facilitate the development of the crops and to help to sustain other useful ions such as Ca_2^+, Mg_2^+, PO_3^{4-}, Mn_2^+, Fe_2^+, etc. [46]. Statistics showing a comparison between the rainfall of 1985 and 2016 (Figure 11) for the United States indicates an increase of pH level (still under 7, acidic side) in rainwater in recent years.

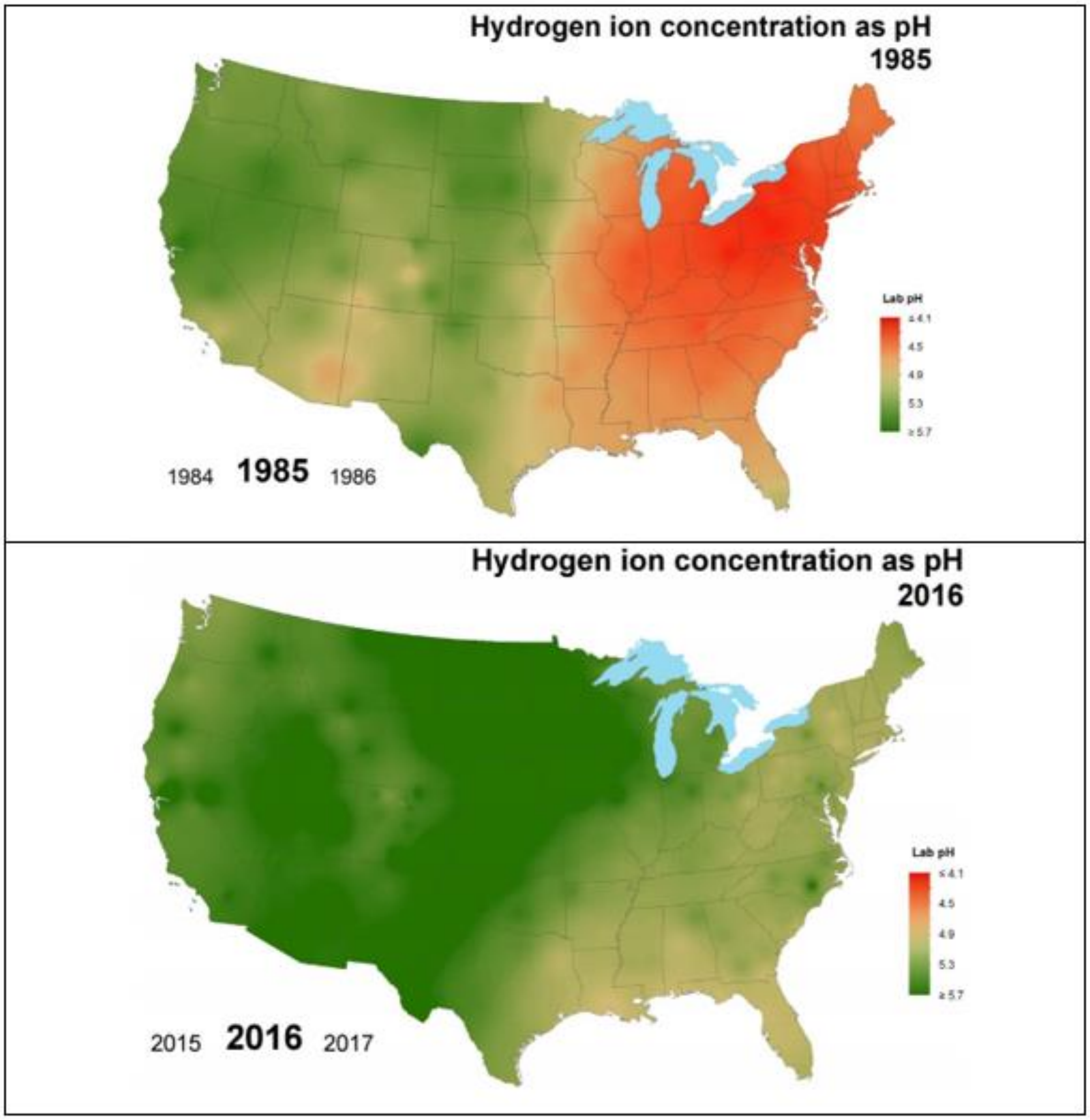

Figure 11: Comparison for Hydrogen ion concentration as pH in the rainfall between 1985 and 2016 for United States indicates increase of pH level [24].

The effect of pH for hydroponic farming is shown in Figure 12, and the recommended pH level stated here is 5.6-6.2 [47].

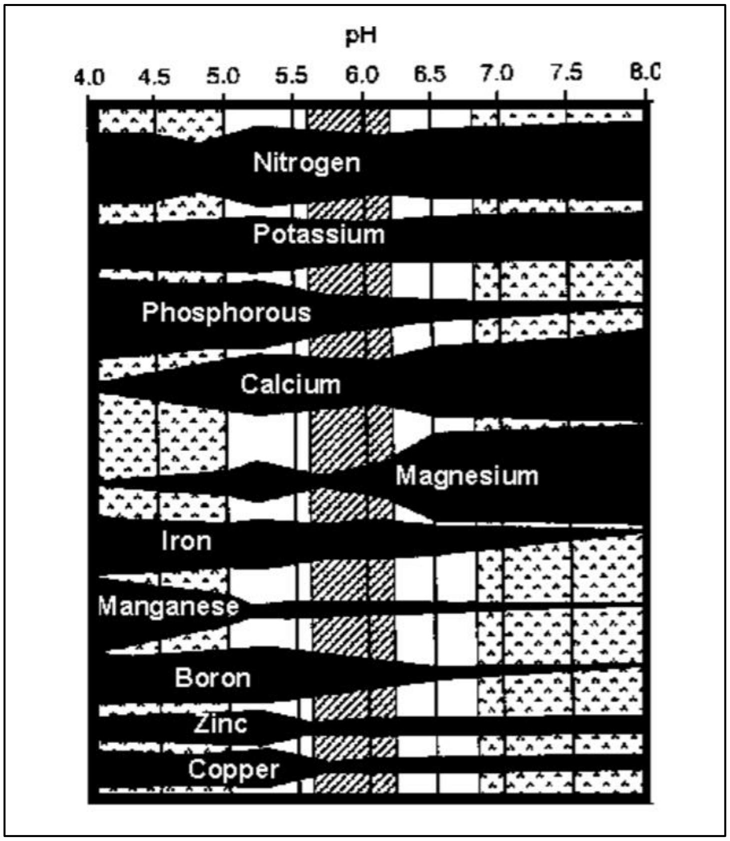

Figure 12: The availability of different plant nutrients at different pH levels [47].

Electrical Conductivity: In other words, known as electrolyte conductivity and salinity represents the water quality to understand the amount of salt concentration that directly affects plant growth, development, and production. The same book refers that 1.5-2.5 dS/m (1 dS/m = 10^3 μS/cm) is the ideal range for the nutrient solutions given that higher EC hinders the plants from absorbing nutrients by increasing osmotic pressure and lower EC affects negatively to the plant health and production. However, different plants have different thresholds for EC to grow, but reasonable control of EC improves the quality of vegetation. Table 1 below is showing the threshold values for different salinity groups that can grow certain crops:

Table 1: Different salinity groups that can grow certain crops. [46]

Salinity Group	Threshold EC, (dS/m)	Example of crops
Sensitive	1.4	lettuce, carrot, strawberry, onion
Moderately sensitive	3	broccoli, cabbage, tomato, cucumber, radish, pepper
Moderately tolerant	6	soybean, ryegrass
Tolerant	10	Bermuda-grass, sugar beet, cotton

The composition of anions and cations: Toshiki Asao (2012) showed in his edited book that researchers found there should be a right balance of cations and anions in the nutrient solution used for hydroponics. Sometimes, even deep-sea water can mix with nutrient solutions because many of the ions are abundant in that water. N, P, S, K, Ca, and Mg are the most significant nutrients which can be found in the ionic form of NO_3^-, $H_2PO_4^-$, SO_4^{2-}, K^+, Ca^{2+}, Mg^{2+}, etc. However, the plants can absorb nutrients even at a low concentration and do not get affected much even if the concentration is reduced by 50%. On the other hand, high concentrations might lead to toxic effects due to the plants' high intake of nutrients. However, there are few exceptions when too low concentration does not meet the minimum demand of plants and where too high concentration (raised to 200%) resulted in early flowering of plants.

Water is treated in for drinking purposes by the public drinking water system in the United States, which follows the steps shown below in Figure 13. In this treatment system along with other chemicals, Chlorine or Chloramines are used to make this water safe to drink by killing potential germs [12].

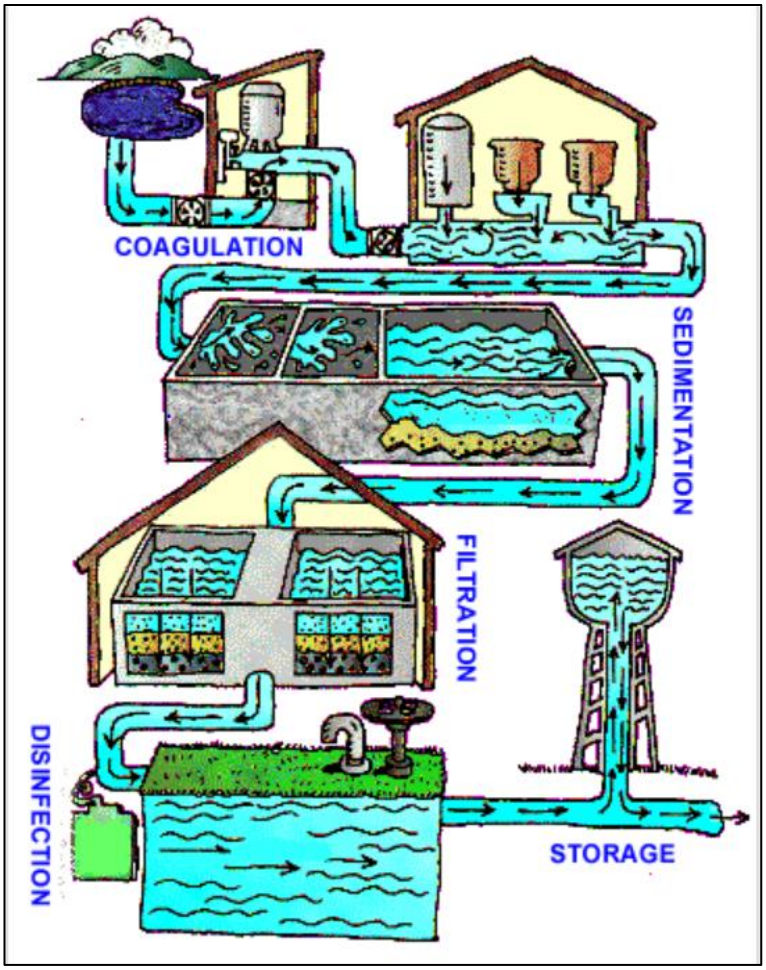

Figure 13: A schematic diagram for a typical water treatment plant [12]

But this Chlorine or Chloramine can be detrimental for plants being dissolved in the nutrient solutions. Studies showed that uncontrolled chloramine concentration or exposure for a limited time of more than 1 hour could cause root browning, wilting, and in some cases, hinder plant growth entirely [48]. These are the reasons why the water used for vertical farming needs to be pure so that nutritional adjustment and toxicity elimination are possible.

1.3.6 *Design of Water System*

Research has been performed at different times to develop suitable models for water systems, including a rain harvesting system to meet industrial areas or households' demands. Designing industrial networks to reduce freshwater usage and wastewater discharge has been proposed by mathematical programming-based techniques [49]. Based on process input and output variables, such as flow rate and concentration, the water network has been developed from water sink to the points of usage shown in Figure 14 below [50].

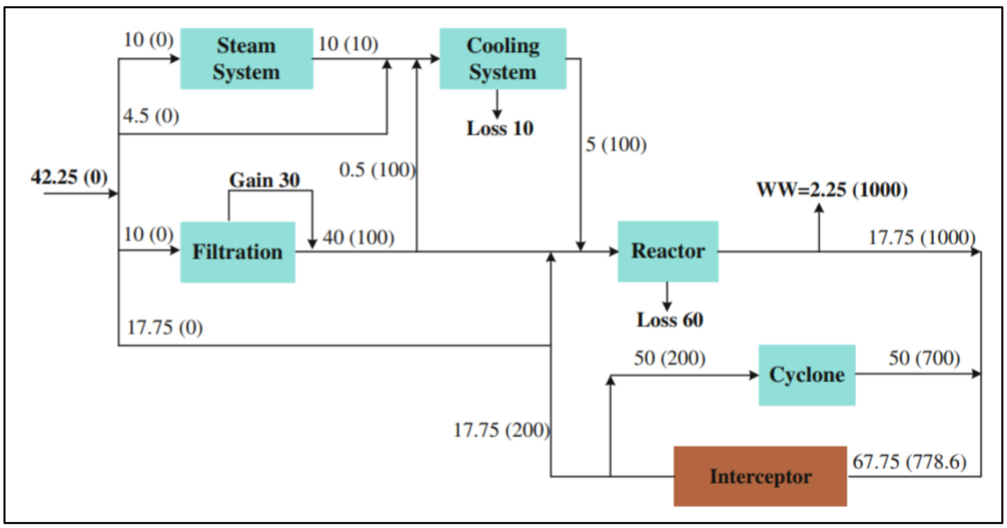

Figure 14: An optimal water network system with one interceptor with a fixed outlet concentration model [50].

Also, water connection network including connections among resources, interceptors, process units, and waste was developed [51], a mixed-integer nonlinear program was developed through a computational study using GAMS/BARON for a petroleum refinery water system where 27% water savings were attained [52]. Mathematical programming model was implied for improving the design of water grids that include property interceptors such as composition, toxicity, pH level, density, viscosity, and oxygen demand [53] as well as configuration items such as segregation, mixing, recycle, bypass, stream treatment and environmental constraints [54]. A study in Seoul, South Korea, reveals the important design parameters: the catchment area, rainfall, tank capacity, water demand (Figure 15), and operational parameters such as rainwater use efficiency, water-saving efficiency, cycle number, etc. Based on meeting non-potable demand by the RHS system for a dormitory complex at Seoul National University (SNU), they suggest that the ratio of tank volume to catchment area should be between 0.03~0.08 in terms of rate of change in rainwater use efficiency [55].

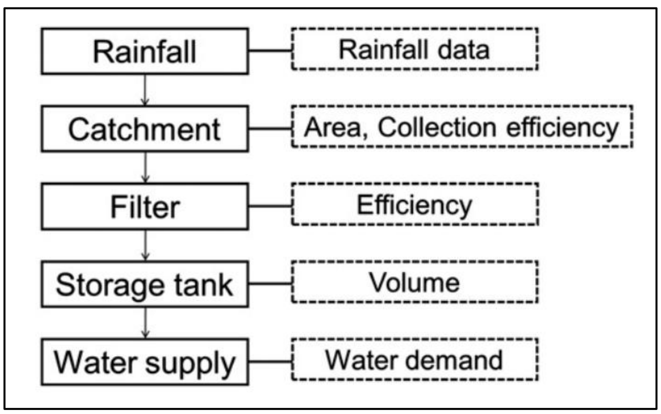

Figure 15: Design components of a rainwater harvesting system [55].

However, no matter what the application type or focus stands, the ultimate target of design for any water system is to meet the demand by its supply system.

2 FEASIBILITY OF INTEGRATED SYSTEM

2.1 Statement of Problem and Hypotheses

This chapter describes the design, development, and assessment for hypothesis 1: Based on the historic precipitation in San Marcos area and performance of the AWG systems, an integrated system of AWG (always ON status) and rainwater, brings more consistency to water production And for hypothesis 2: Addition of Smart AWG (ON only when rainfall for the month is below long-term average) to RHS, brings more stability to water production than the addition of always ON AWG to RHS.

2.2 Methods and Materials

The methods and materials for this section consist of mainly historical data analysis for further investigation.

1) Four years (2014-2017) of historical data of precipitation are collected for the local area (San Marcos, TX), and the following calculation is done to convert the rainfall data into the amount of water that can be collected with existing catchment area. The amount of rainfall is measured in depth of water that reaches into the ground. The volume of water is calculated by multiplying this depth with the catchment area.

   Collectable volume of water (cubic-in) = rainfall*catchment area

2) Historical data of AWG for the same years are collected for the same area. In this case, the water volume that is generated by the AWG is directly measured from its water tank.

3) Both rainfall and AWG data are also converted into the unit of gallons to acquire better understanding compared to a 3000-gallon water tank and then scaled to a comparable

measure (e.g., feature scaling to obtain values between 0 and 1, the equation used for this calculation is, $x_{new} = \frac{x - x_{min}}{x_{max} - x_{min}}$ [56]).

4) Data are combined for both sets, and the coefficient of variation (CV) is calculated for the data. Graphs are drawn to present comprehensive interpretation of **the integrated system** with **always ON AWG** operation.
5) The logic of smart AWG (ON only when rainfall for the month is below long-term average) is applied to the collection and enhanced (normalized) data of precipitation and AWG production.
6) Data are combined for this set again. Complete data is included in Appendix A.
7) The coefficient of variation (CV) is calculated for this set of data. Graphs are drawn to present a comprehensive interpretation of **the integrated system** with **smart AWG** operation.

2.3 Results

The results for hypothesis 1 and 2 are discussed in two different sections below. These two hypotheses are basically distinguishing the difference between adding the AWG as either keeping it always on or turning it on only when there is a water demand, and the atmospheric condition is favorable for water generation.

2.3.1 *Results for Hypothesis 1*

*Based on the historic precipitation in San Marcos area and performance of the AWG systems, an integrated system of AWG (**always ON** status) and rainwater, brings more consistency to water production.*

1) A sample calculation for measuring the volume of water is shown in Table A-1 in Appendix A.

Collectible volume of water (in^3) = rainfall*catchment area = rainfall in inch*285129 sq-inch (roof measurements are shown in Figure 16; length = 1440 in, width = 198.00625 in, area = 1440*198.00625 = 285129 in^2)

The volume of water is then converted into a unit of liters. (1 in^3 = 0.0163871 liter)

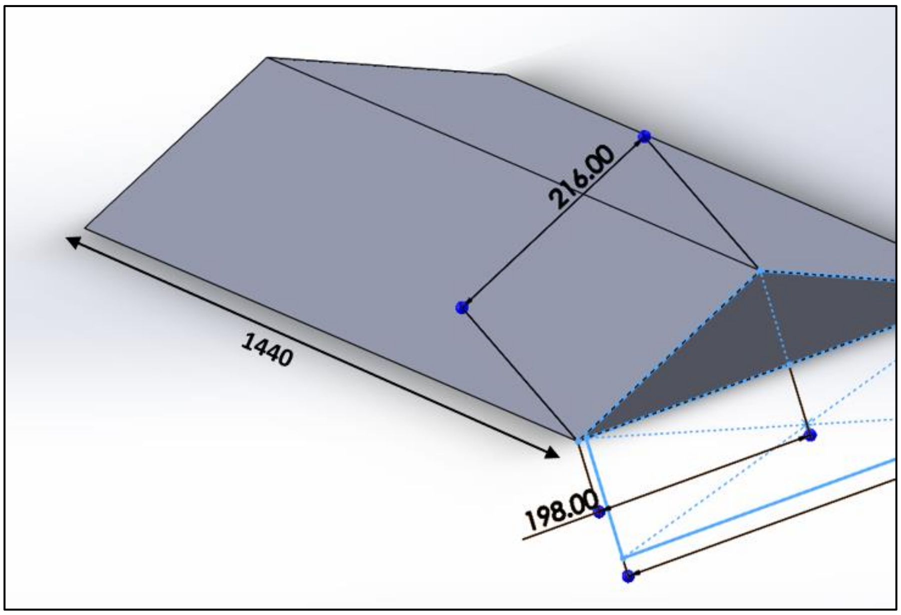

Figure 16: Roof catchment area measurement.

2) Similarly, a sample of historical data of water generation by AWG is shown in Appendix A in Table A- 2 . A comparison graph of normalized values for rain and AWG is shown below in Figure 17. When the blue line (rain) is down, the orange line (AWG production) is up and vice versa several times in the 4-year range of data collection. This observation leads to the idea that these two systems might be complementary.

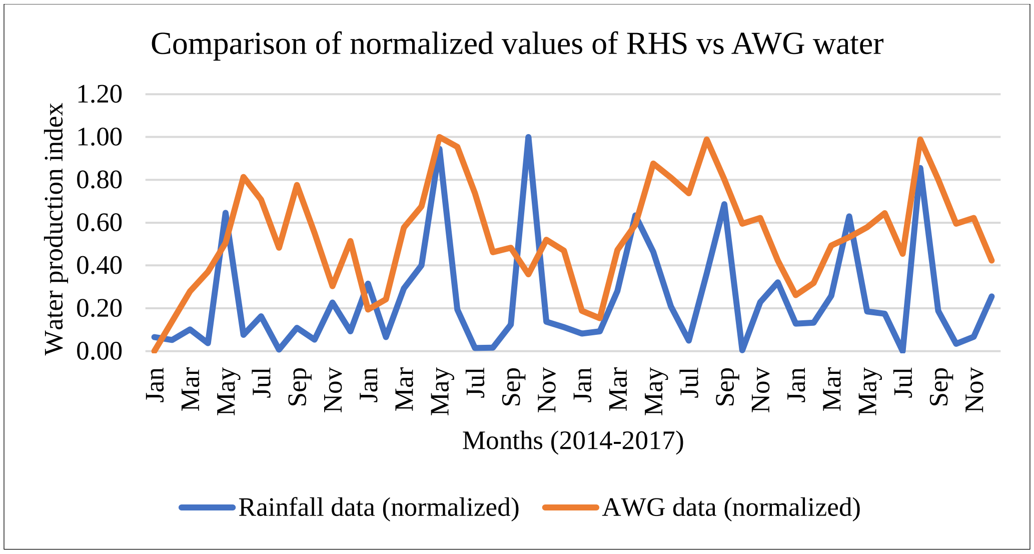

Figure 17: Comparison between RHS vs AWG water data. This graph shows that the systems reach their peak production in opposite seasons several times.

3) A sample of RHS and AWG- normalized data and the sum of the normalized values are shown in Table A-3 in Appendix A. This enhancement makes it easy to perceive the data based on the range 0-1, considering the lowest water amount 0 and the highest amount is 1 (highlighted in orange).

4) Table 2 illustrates a summary performance of the RHS and AWG on the original scale and normalized results. As shown in this table, the addition of AWG (**always ON** status) to rainwater, brings more stability to water production by the integrated system compared to rainwater harvesting alone (column heading, E=A+B).

CV (A+B) = 0.51 < 1.00 = CV (A)

Figure 18 shows the graphical representation of water yield from rainfall + always 'ON' AWG.

Conclusion: Hypothesis-1 claim is accepted.

Table 2: Four years (2014-2017) of rainfall and AWG water generation data in original and normalized format including the coefficient of variance for San Marcos, TX.

		A		B	C	D = A+C	E = A+B
	Rain (liter)	Rain (normalized)	Total AWG/month (liter)	AWG (normalized)	Smart AWG	Sum of Normalized Data (Rain+ Smart AWG)	Sum of Normalized Data (Rain+AWG)
Standard Deviation	17236.61	0.25	86.82	0.24	0.31	0.26	0.40
Mean	16462.03	0.24	271.81	0.54	0.34	0.58	0.78
Coefficient of variation (Std /Mean)	1.00	1.00	0.32	0.44	0.91	0.44	0.51

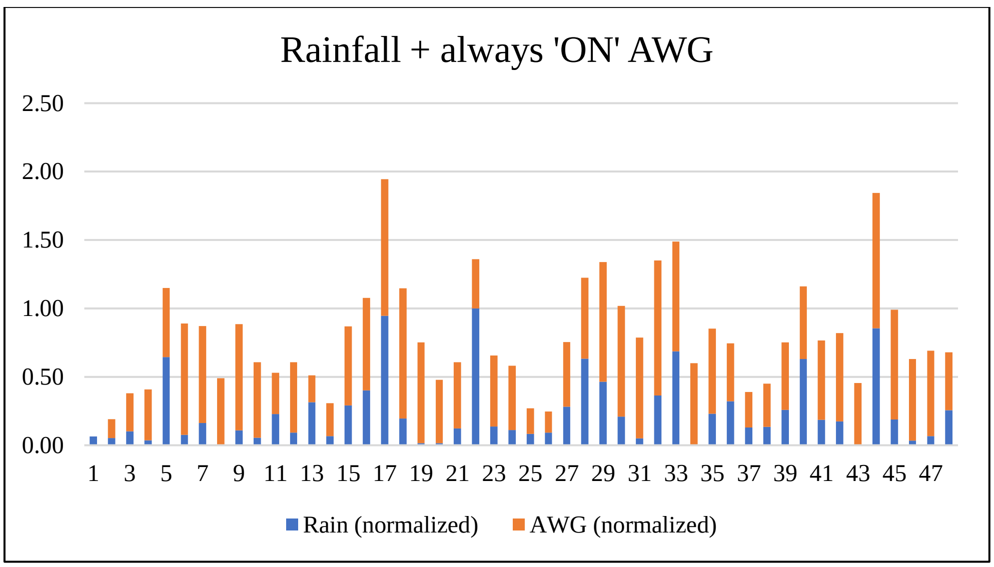

Figure 18: Graph showing water yield from Rainfall+ always 'ON'AWG.

2.3.2 *Results for Hypothesis 2*

Addition of ***Smart AWG*** *(ON only when rainfall for the month is below long-term average) to RHS brings more stability to water production than the addition of* ***always ON AWG*** *to RHS.*

1) As shown in Table 2, the addition of *Smart AWG* (ON when rainfall is below historical average) to rainwater brings more stability to water production than the reliance on *rainwater alone* (column heading, D = A+C).

   CV (A+C) = 0.44 < 1.00 = CV (A)

   Conclusion: Part 1 of Hypothesis-2 claim is accepted.

2) Similarly, from Table 2, the addition of *Smart AWG* to rainwater brings more stability to water production than the addition of AWG (*always ON* status) to rainwater.

   CV (A+C) = 0.44 < 0.51 = CV (A+B)

   Conclusion: Part 2 of the Hypothesis-2 claim is accepted.Figure 19 and Figure 20 shows graphical representation of comparing Smart AWG with other system situations.

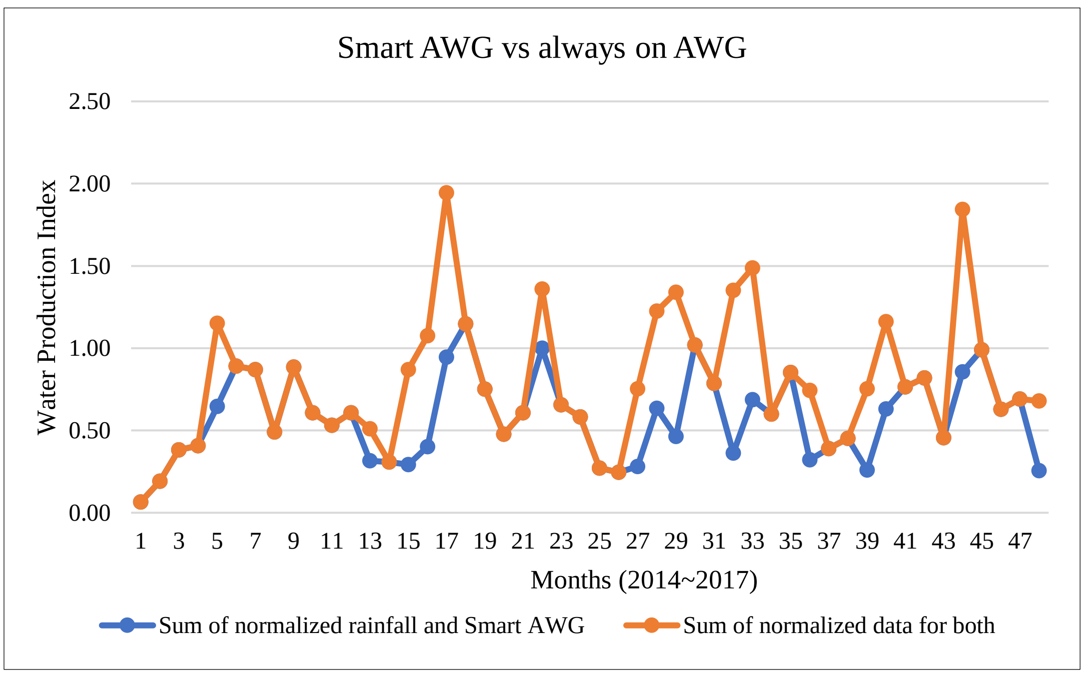

Figure 19: Graph showing how Smart AWG versus Always ON AWG operation is different when integrated with rain harvesting system.

The difference between the lines are the differences between smartly operated AWG and always ON AWG. The blue plot having less up-down than the orange one indicates that it is better in consistency.

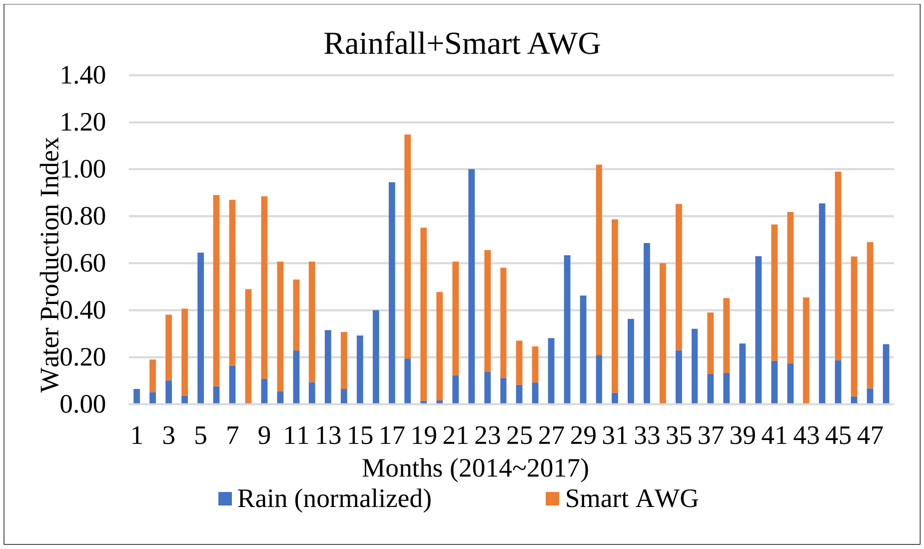

Figure 20: Graph showing water yield from rainfall+ Smart AWG.

Notice the absence of orange or blue bars for some data indicating that the system sometimes adapts to either RHS or AWG based on the situation, and sometimes, both.

3 INTEGRATED SYSTEM AUTOMATION

3.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 3: *The integrated system (RHS and AWG together) can automatically collect, store, filter, deliver, and supply water to the point of use.*

3.2 Methods and Materials

For a better explanation, the integrated water system is divided into two sections: 1. Collection/Generation side, and 2. The delivery/consumption side (Figure 21) and each section are divided into two subsections: Mechanical and Electrical System. Design, development, coding for Arduino Uno, and electrical connection modification- all are performed separately for each part of the system in the following steps.

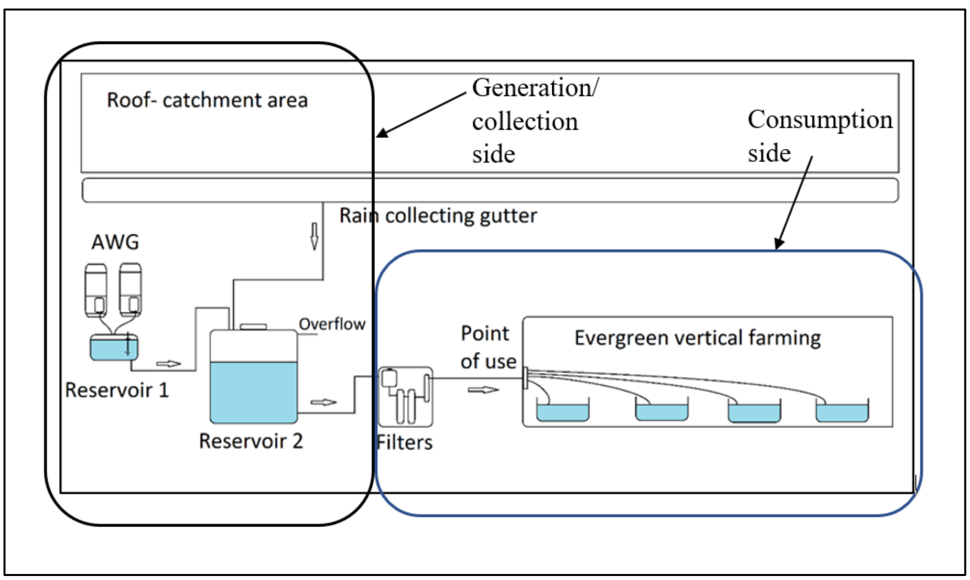

Figure 21: A preliminary schematic diagram of the integrated structure.

1) RHS and AWG are evaluated independently to identify and study their essential sub-systems such as collection and generation, storage, replenishment, filtration,

preservation, and delivery. The water systems contain few similar components such as filter, storage tank, treatment system, pump, power supply, etc. We use these standard components to be unique for both systems instead of having them in two separate systems. Figure 21 shows a schematic diagram of this integration.

2) A systematic product development process is followed to generate, select, refine, and integrate concepts.
3) Fabrication and assembly of the mechanical and electrical components into the integrated system and the supply system to end-user (refilling vertical farming reservoirs) are done in an experimental setup. Upon confirmation of the coding, wiring, and working components, the systems are introduced on-site.
4) Smart system logics are applied for improvements such as automatic refill tank with float sensors, electromagnetic solenoid valves, and continuous flow with a feedback system, sensor dependent operation, pump operation, and complete real-time automation.

3.2.1 *Collection/Generation*

The collection/generation side of the system consists of the main reservoir which stores the collected rainwater from the catchment area as well as the generated water by atmospheric water generator. The mechanical and electrical systems for this side are as follows.

3.2.1.1 Mechanical System

1) The RHS is installed in the Freeman Center (San Marcos, TX) with a 3000-gallon capacity reservoir and a filtration unit consisting of a pressure tank, carbon filter, reverse osmosis, and ultra-violet unit shown in Figure 25(c). The gutter system

installed along the roof collects the rainwater directly from the catchment area and delivers it to the main reservoir.

2) The float sensor inside the main reservoir is installed in such a way that when the water level goes below 1000 gallons, it turns on a 110V power outlet. This power outlet is used to power the electrical system for the generation side.

3) Two commercial Atmospheric Water Generators ‘AquaBoy Pro-II’ made by Atmospheric Water Solutions, Inc. has been chosen to integrate with the RHS. Each can produce 2-5 gallons of water per day depending on the atmospheric conditions and has a warranty of 2 years.

4) In the AWG, the generated water keeps circulating inside its closed system, and the water can be retrieved from a tap by pushing a touchpad. Hence, the modification of this closed system is done to let the generated water come out automatically to deliver it to the main reservoir. AWG modification is performed by disconnecting the water line from its bottom tank and then redirected it to an outer secondary reservoir. The top tank level sensor is disabled after doing the first priming.This modification eliminates unnecessary energy consumption by its water pump operation, filtration, and recirculation.

5) A wooden frame infrastructure has been fabricated to place the AWGs on the top shelf and the temporary collection reservoir in the bottom shelf to aid the flow of the generated water by gravity.

6) The integrated system is designed and drawn in a 3D CAD model using SolidWorks software on a personal computer.

3.2.1.2 Electrical System

1) A schematic diagram is drawn to illustrate all the connections (power supply, digital signal, and water flow) in the collection/generation side.
2) In the water generation side, the information from the estimated water production plot shown in is used to decide on the range of temperature (55~120 deg F) and relative humidity (30~100%) combination. Arduino coding was developed according to this range for operating AWG based on a real-time feedback system from the atmospheric condition.
3) The secondary tank that collects the AWG generated water consists of a float and a submersible water pump. Upon receiving the level up a signal from the float of this tank, the Arduino turns on the pump through a relay switch and runs the pump for 15 minutes to deliver the collected water to the main reservoir. The floating structure shown in Figure 22 is also designed and drawn in SolidWorks software and finally fabricated by using the PVC pipe and fittings that are available on-site.
4) The electrical system for generation from AWGs can be stopped by either meeting the level up signal from the main reservoir, which will cut-off the 110V power supply or being the environmental condition entirely unfavorable for operating the AWG systems. The logic flow chart for this electrical system is developed.

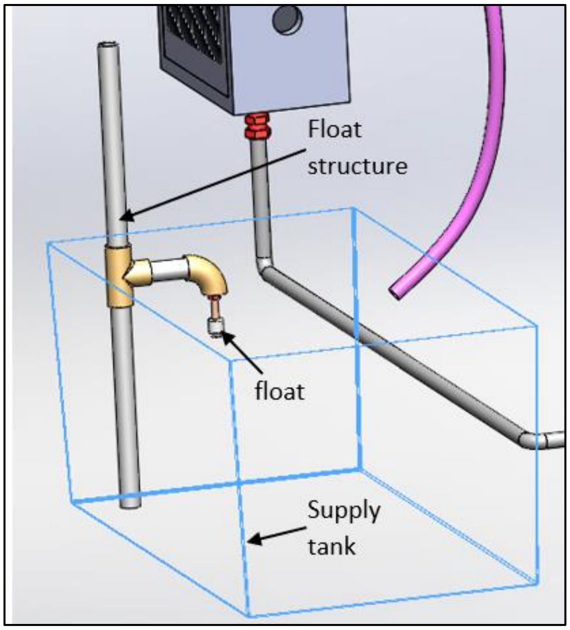

Figure 22: 3D CAD model for the float with the tank.

3.2.2 *Delivery/Consumption*

The delivery side consists of the filtration system to the point of use (vertical farming) where eight supply tanks are installed to regulate consistent water flow to the plants. The mechanical and electrical systems for this side are as follows.

3.2.2.1 Mechanical System

1) To facilitate water to all eight supply tanks, a water flow distributor is added with a total of 12 outlet lines with manual shut-off valves. A solenoid is installed on each line for respective tanks.
2) The same float structure with PVC pipe (Figure 22) is installed in the supply tanks having the float height of 13 inches from the bottom of the tanks.

3.2.2.2 Electrical System

1) A schematic diagram is drawn to illustrate all the connections in color coded flow lines (power supply, digital signal, and water flow) in the collection/generation side using diagrams.net.
2) Automation in the consumption side is introduced to maintain a constant level of water in the supply tank. Since the consumption of water in 8 racks of vertical farming might vary due to different watering schedules and different species and the number of plants for each rack, each tank might need to refill in a different frequency. Digital float installed in each tank sends a signal to the Arduino that controls and refills water level.
3) Arduino programming is developed, uploaded, and tested in an experimental setup to ensure that it works as expected. Since 16 pins are required for a total of eight input pins from floats and eight output for the tanks and the Arduino having the limitation of 12 digital input/output pins, two Arduino Uno boards are considered for connecting four floats and four solenoids to each.
4) The logic flow chart for one tank with a float-solenoid system is developed based on the coding in diagrams.net.
5) A schematic for the circuit diagram showing all the wiring of all the components is drawn in diagrams.net. Test and debugging are carried out in an experimental setup, and then the system was introduced on-site.

3.3 Results

The results are listed the same way as the methodology was carried out considering mechanical and electrical each system for both collection and delivery sides.

3.3.1 *Collection/Generation*

The main component of this side is the main reservoir (reservoir-2 in Figure 21). Whether the water is coming from rainfall or from the AWG generation, it is stored in this 3000-gallon tank. The mechanical and electrical systems are designed to support this storing process.

3.3.1.1 Mechanical System

1) The Figure 23 below shows the rain gutter installed along the edge of the roof with the 3000-gallon tank and the filtration unit.

Figure 23: (a) Rain gutter & reservoir, (b) Vertical farming container, (c) Filtration unit.

2) Figure 24 shows the selected AWGs and the plot of estimated water production based on temperature and humidity provided in the manufacturer's manual.

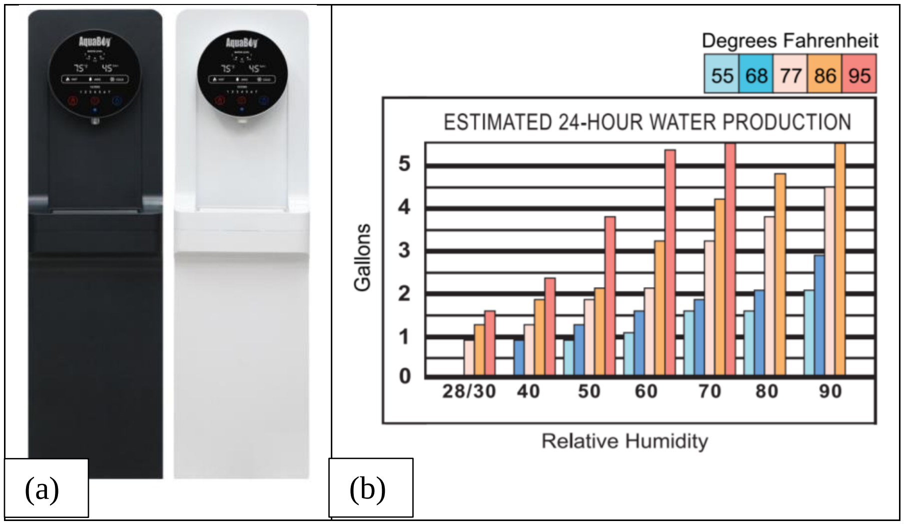

Figure 24: (a) AquaBoy Pro-II [57]; (b) Estimated water production graph based on temperature and humidity [58]

3) The 3D CAD models in the following figures show different components of the smart integrated water system:

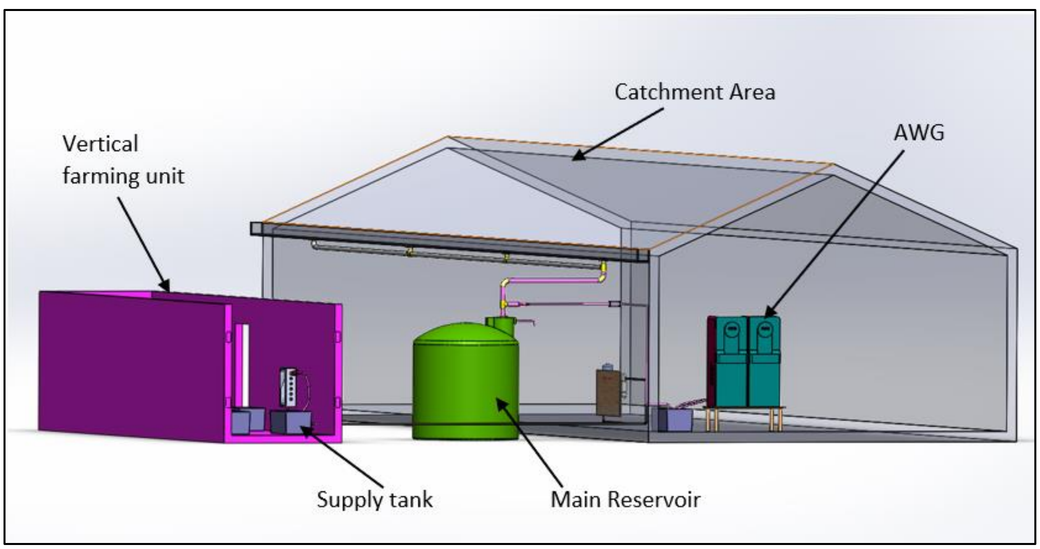

Figure 25: The integrated water system for the vertical farming unit.

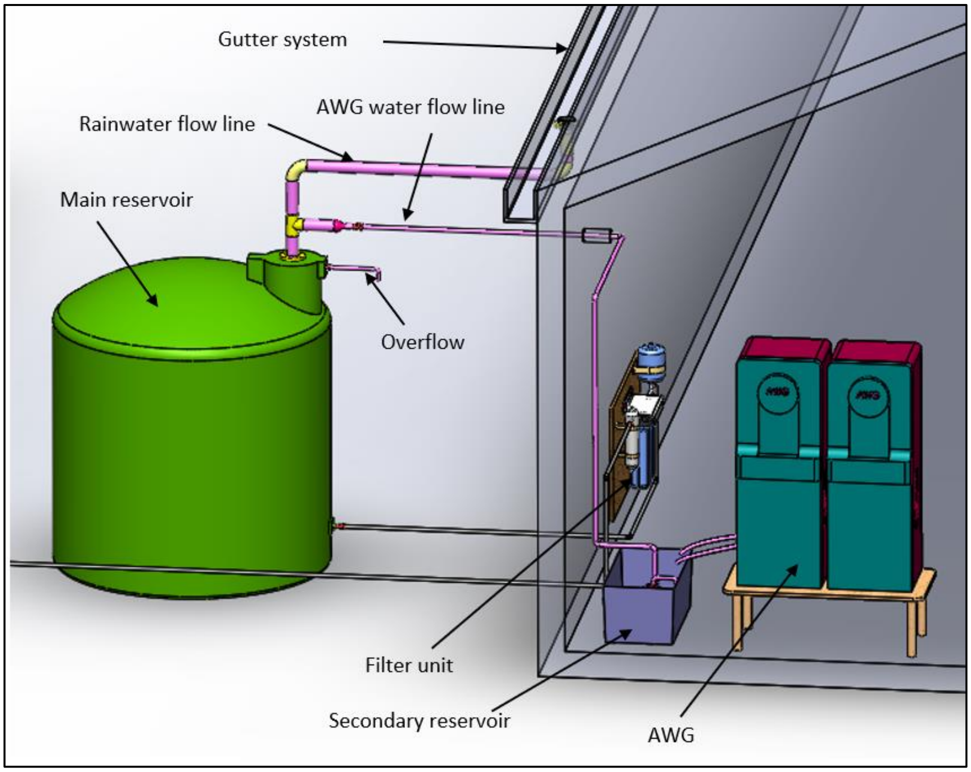

Figure 26: The secondary reservoir collects water from AWGs, and the Main reservoir stores water both from rainfall and from the secondary reservoir.

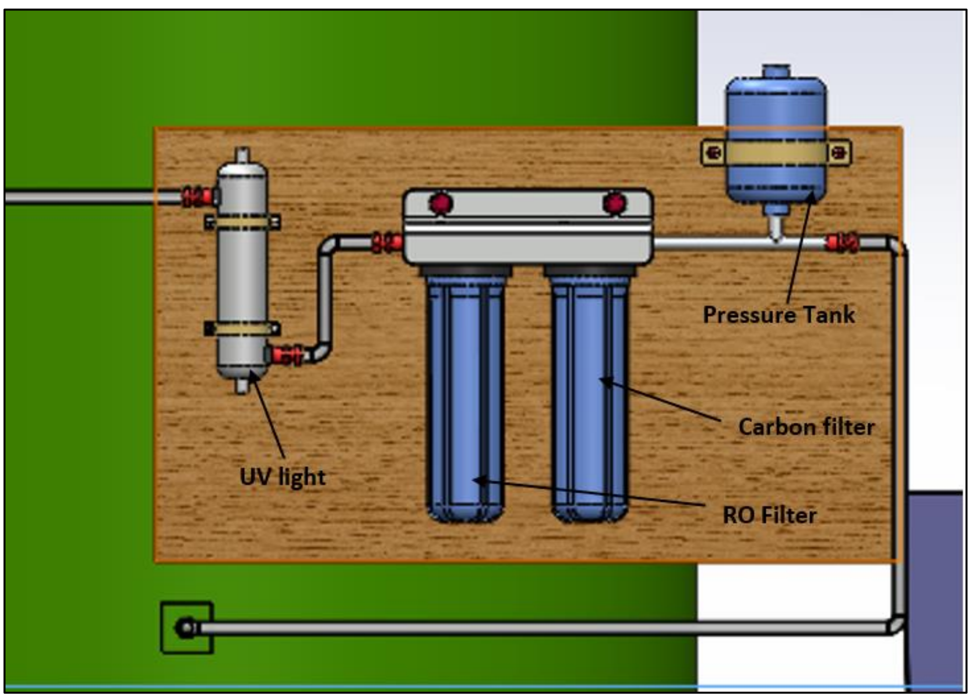

Figure 27: Details of the filtration unit.

3.3.1.2 Electrical System

1) The schematic drawing of the integrated system for collection/storage side is shown below:

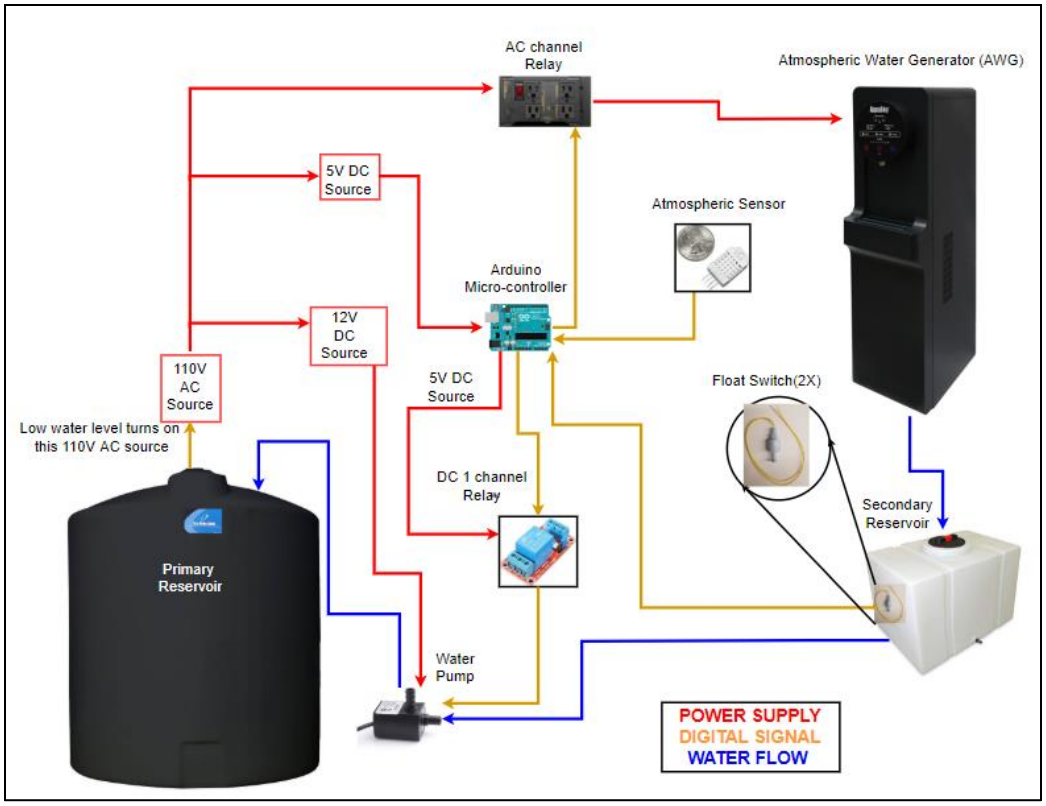

Figure 28: Schematic drawing of the generation/collection side with automation.

2) The support structure for the float is shown in Figure 22. The fabrication was easy to do with no significant disadvantage and has the following advantages:

- Convenient to assemble or disassemble into the tank.
- No intensive machining is required.
- Sturdy and easily replicable.
- Protection for float wiring from water damage.
- It can be replicated, adjusted to any height easily.

3) Arduino program (Figure 29) for operating the AWG based on the real-time feedback system from the atmospheric condition is shown below. Complete algorithm is included in Appendix C, Table B-1. This logic system first assesses if the environmental condition is in favor or not to run the AWG and decides upon turning on/off the AWG and thus avoids unnecessary consumption of energy. Therefore, it becomes a smart AWG in terms of operation.

```
void loop() {
  dht.readHumidity();
  dht.readTemperature();
   // Check if any reads failed and exit early (to try again).
  if (isnan(dht.humidity) || isnan(dht.temperature_C)) {
    Serial.println("DHT sensor read failure!");
    return;
  }

  Serial.print(dht.humidity); Serial.print(" %\t\t");
  Serial.print(dht.temperature_F); Serial.print(" *F\t");
//Ranges of relative humidity and temperature are defined
  if(dht.humidity>30.00 && dht.humidity<100.00){
    if (dht.temperature_F>55.00 && dht.temperature_F<120.00){
    digitalWrite(13, HIGH); //Turn on AWG
    }
  }

  else{
    digitalWrite(13, LOW); //Turn OFF AWG
  }
```

Figure 29: Coding to read real-time atmospheric condition (relative humidity & temperature) to ON/OFF the AWG.

4) The Arduino program (Figure 30) using feedback from the float switch to turn on the water pump is shown below. Once the “Water level is up” signal is received, the pump is turned on for 20 minutes to transfer the water from this secondary reservoir to the main reservoir.

```
//controlling the pump by the float
   if(digitalRead(FLOAT_SENSOR) == HIGH)//water level is up
  {

    //Serial.print("Water level is up");
    digitalWrite(pump_1, HIGH);// start the pump
    delay(20*60*1000UL); //pump stays on for 20 min
      }

  if(digitalRead(FLOAT_SENSOR) == LOW)//water level is up
  {
    digitalWrite(pump_1, LOW);// start the pump
      }
```

Figure 30: Coding to pump the generated water from AWG into the main reservoir by a submersible pump.

5) The logic flow chart combining both logics- the AWG and the pump control is shown in Figure 31. The atmospheric sensor assesses the relative humidity (RH%) and temperature (temp) of the surroundings and the float assesses the water level in the reservoir 1 (Figure 21) to make decisions accordingly.

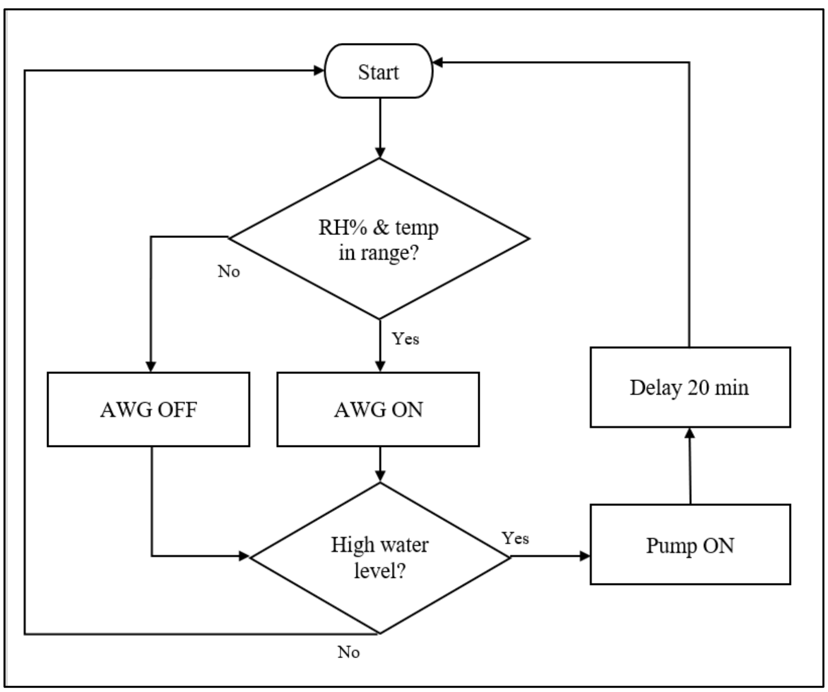

Figure 31: Logic flow chart for the collection/storage side.

6) Details of established connection among the electrical components (Figure 32). In Arduino, pin 2 is the input from the atmospheric sensor, and pin seven is from the float sensor. Pin 13 and pin 8 are the outputs to operate AWG and the pump, respectively.

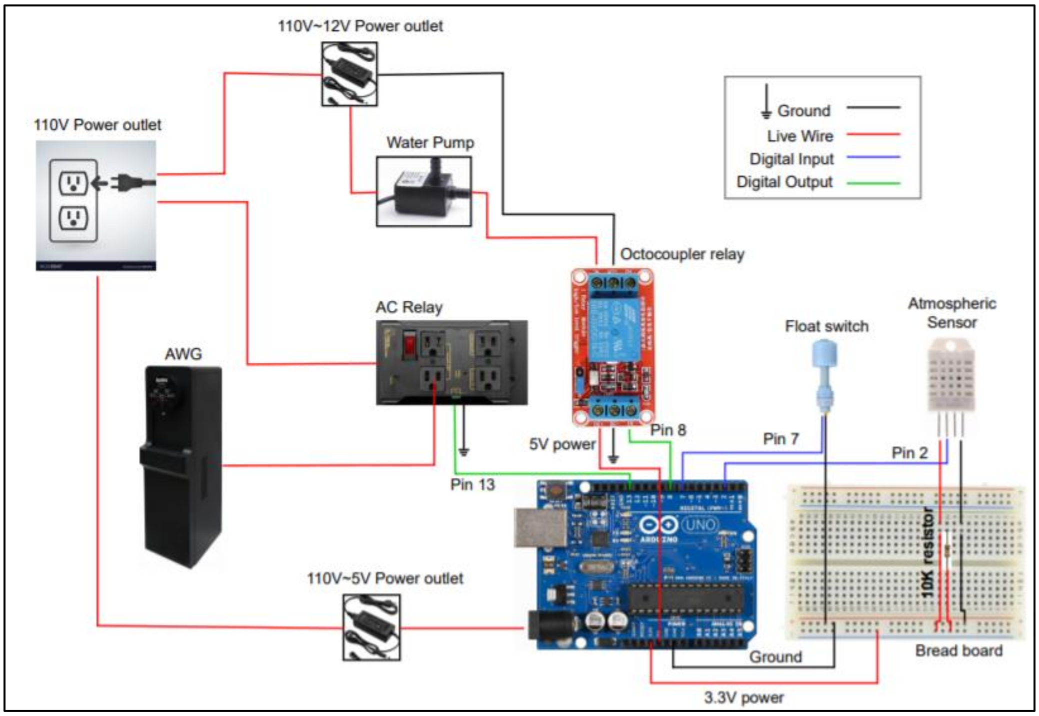

Figure 32: Circuit diagram for generation side developed in diagrams.net.

The main purpose of this delivery side is to refill the eight supply tanks that stream nutrition solution to the plants placed vertically in respective racks. The mechanical and electrical components are designed to focus on the automatic refill process of these supply tanks so that a consistent water supply is available for watering the plants.

3.3.2 *Delivery/Consumption*

The main target for delivery side is to automatically supply and refill supply tanks. Nutrition for plants that grows in the vertical farming, are added in these tanks.

3.3.2.1 Mechanical System

1) The delivery system consists of a water line that goes through the pressure tank and filtration set and finally to the vertical farming unit. The line is then divided into a total of 12 outlet lines shown in
2) Figure 33(a) with manual shut-off valves that can deliver water directly to the supply tanks or can be used for cleaning or other purposes.
3) The eight outlets connected to the eight supply tanks also have electromagnetic solenoid shut-off valve shown in
4) Figure 33(b) to control the water refill process to the respective tanks automatically. Figure 34 illustrates how the solenoid valve is installed between the water line to control the water refilling process.

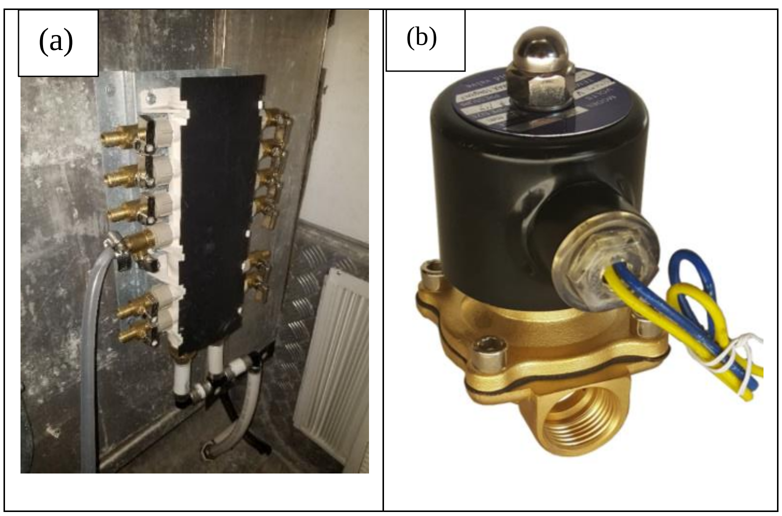

Figure 33: (a) 12 outlet lines with a manual shut-off valve for end-of-use water delivery. (b) HFS 12V DC Electric Solenoid Valve.

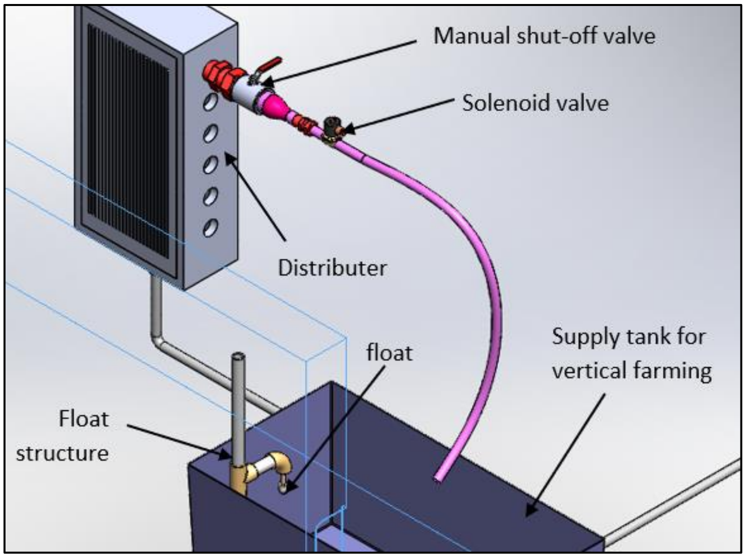

Figure 34: Supply tank, distribution line with manual valve, solenoid, and float structure.

3.3.2.2 Electrical System

1) The schematic drawing of the integrated system for the delivery/consumption side is shown in Figure 35. Automation in the consumption side is introduced to maintain a constant level of water in the supply tank. Since the consumption of water in 8 racks of vertical farming might vary due to different watering schedules and different species and the number of plants for each rack, each tank might need to refill in a different frequency.

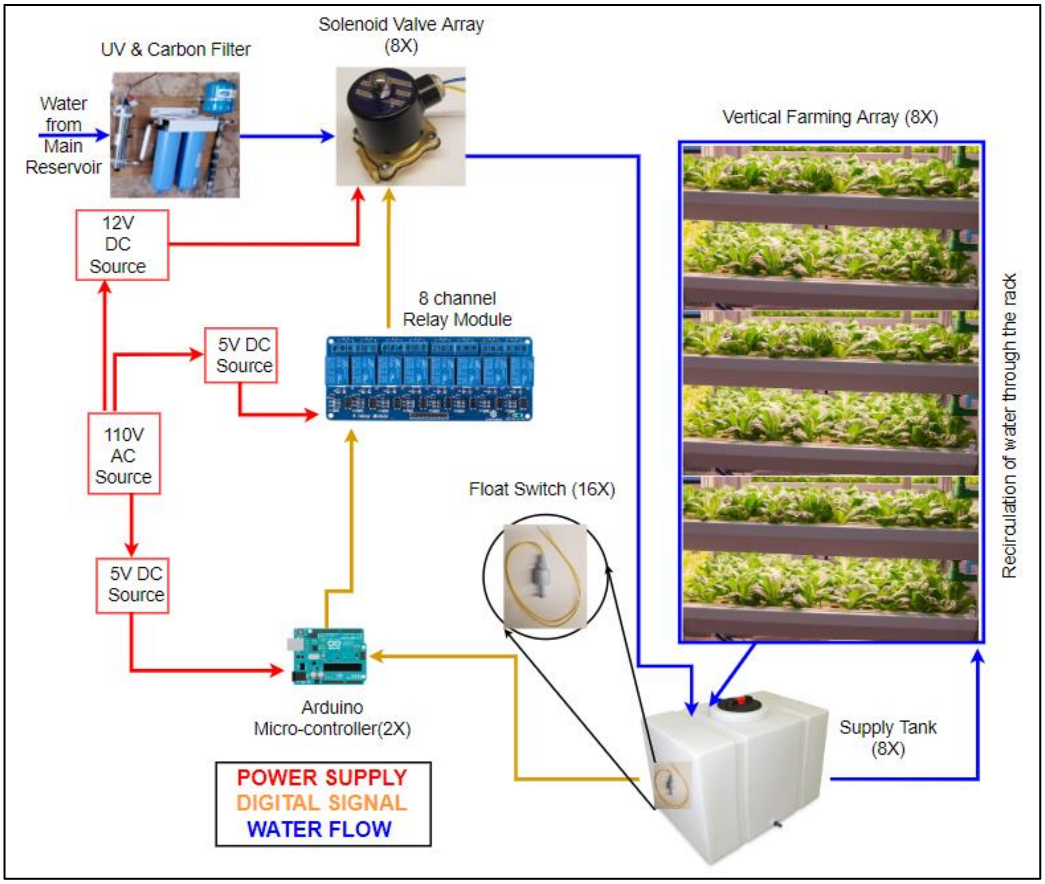

Figure 35: Schematic diagram for the delivery side using diagrams.net.

2) A part of the full coding for Arduino-1 to control four solenoid valves for four tanks is shown in Figure 36. The coding for Arduino-2 is the same, complete algorithm is shown in Appendix C, Table B-2. Each Arduino controls four solenoids taking input for respective float valves for respective supply tanks. If one float signals that low level of water in the tank, the respective solenoid stays open for 5 minutes to allow enough water flow to refill it. To be able to do this, the logic must read all the combinations of four floats in HIGH and LOW positions (total 16 combinations) and act accordingly.

```
void loop()
{
  //Assessing Tank water level simultaneously for all the four tanks

if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW
&& digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  LOW)
   {digitalWrite(solenoid_1,  LOW );digitalWrite(solenoid_2,  LOW );
   digitalWrite(solenoid_3,  LOW ); digitalWrite(solenoid_4,  LOW );
   delay(5*60*1000UL);} // all solenoids stay open for 5 minutes


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW
&& digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  HIGH)
   {digitalWrite(solenoid_1,  LOW );digitalWrite(solenoid_2,  LOW );
   digitalWrite(solenoid_3,  LOW );digitalWrite(solenoid_4,  HIGH );
   delay(5*60*1000UL);} // all open for 5 minutes except solenoid 4


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW
&& digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  LOW)
  { digitalWrite(solenoid_1,  LOW );digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  HIGH ); digitalWrite(solenoid_4,  LOW );
   delay(5*60*1000UL);} // all open for 5 minutes except solenoid 3
```

Figure 36: A part of coding for the floats to control respective solenoids for respective supply tanks.

3) The logic flow diagram for the consumption side shown in Figure 37 for each supply tank is simple. If the water level is low, the solenoid will open for 5 minutes to refill the tank, and this logic is similar for all the supply tanks respective to their floats and solenoids.

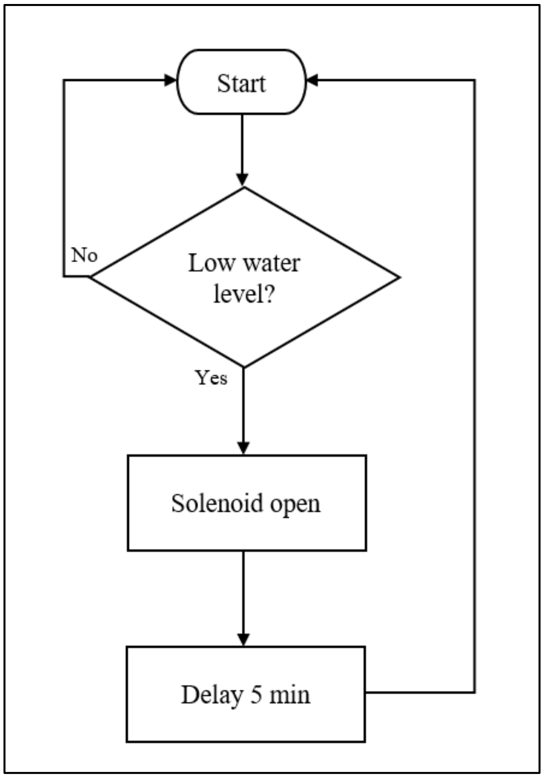

Figure 37: Logic flow diagram for each float-solenoid to refill respective tanks.

4) Details of established connections among the electrical components are shown in Figure 38. Pins 2, 4, 6, 7 are the input pins, and pins 10, 11, 12, 13 are the output for the floats from tank 1-4, respectively, which switches on/off the 8-channel relay to control the respective solenoids. Connection for only one Arduino and individual solenoids is shown in that figure to avoid the cluster of similar components.

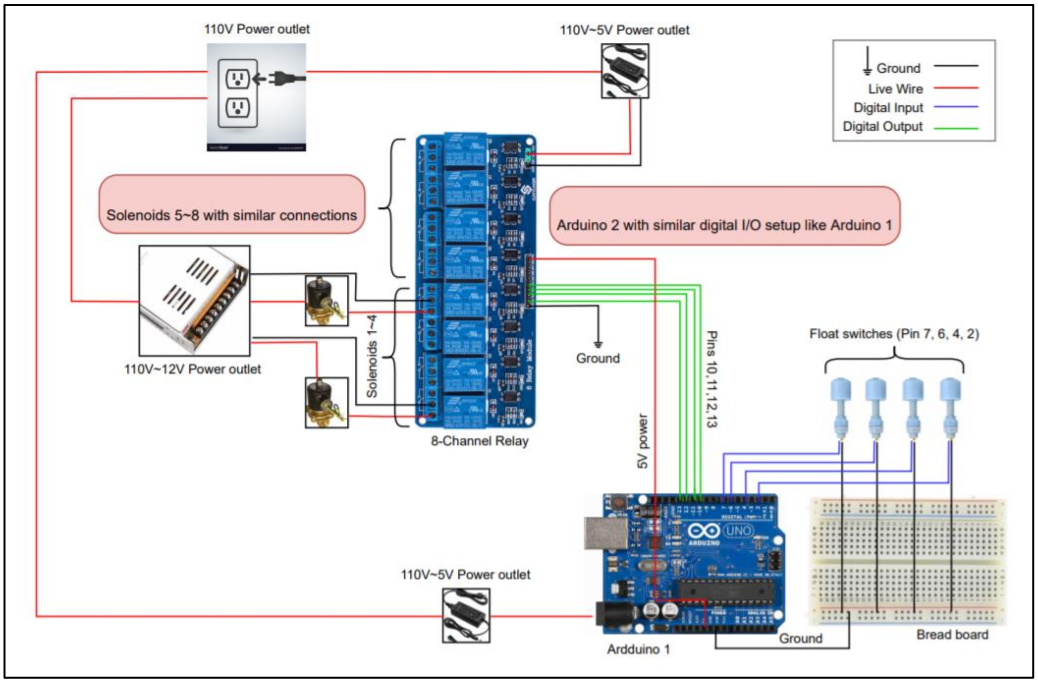

Figure 38: Circuit diagram for wiring of all the components.

4 WATER QUALITY AND COMPATIBILITY

4.1 Statement of Problem and Hypothesis

This chapter describes the design, development, and assessment for hypothesis 4: *This automated system can perform as a superior watering mechanism in terms of water quality and integrate-ability for the automated vertical farming system.*

4.2 Methods and Materials

1) Parameters such as pH level, electrolyte conductivity (µS/cm), Chlorine level (FCl- Free Chlorine and TCl- Total Chlorine), amount of Calcium (Ca^{2+}) and Nitrate (NO^{3-}) ions (ppm) are identified to assess the quality of water affecting the vertical farming in terms of the growth and health of the plants.
2) The water samples from RHS and AWG are separately collected. Also, the same characteristics are tested for samples taken from a San Marcos household supply water, from Freeman Center well water and groundwater from an office facility located in Seguin for comparison purpose. All water samples are collected in airtight glass jars and are immediately closed to avoid any exposure. All the samples are tested instantly to ensure accurate evaluations.

4.3 Results

The results for water quality assessment are summarized in Table 3 for all the parameters. Figure 39 shows the test kits that are used for testing all the samples including test results for Chlorine testing.

1) pH: There is no significant difference in pH level for the listed samples in the table. All the values are between 6.5~7.5. If the preferable range (5.5~6.5) is considered then the AWG, rainwater, and the supply water have the closest values.

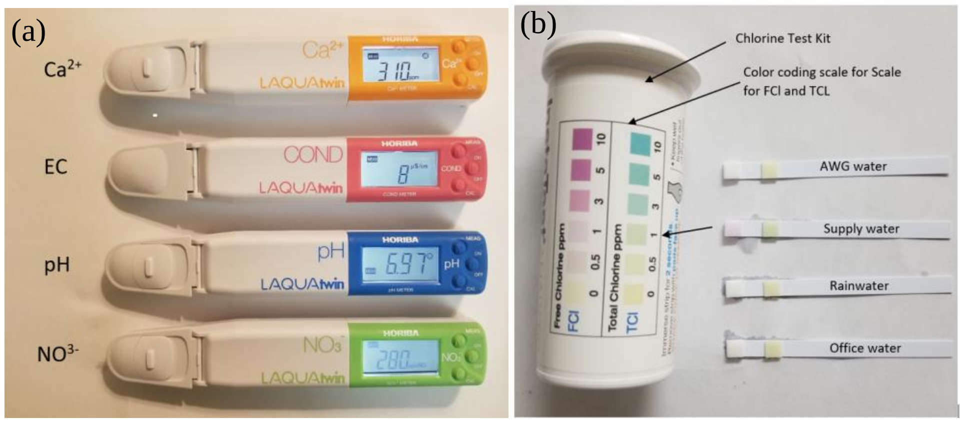

Figure 39: (a) Horiba LAQUAtwin compact testers for ion testing [59], (b) LaMotte 3027-G test strips for Chlorine testing [60].

2) EC and Minerals: AWG water has properties close to distilled water with the lowest EC level and virtually no minerals. The EC (highlighted as green in Table 3) and the mineral level of rainwater are also significantly low, which indicates that for both rainwater and AWG water, the most tolerable EC range of nutrient solutions for plants (1500~2500 µS/cm) can be easily achieved and maintained. However, water samples 3 and 4 have comparatively higher EC (highlighted as pink) and NO_3^- values (acceptable ranges, EC< 775 and $1<NO_3^- <10$, for drinking water [61]). This amount is expected because the groundwater is usually exposed to different minerals, fertilizers, and insecticides due to leaching. Sample 5 having the highest value of EC and NO_3^- (highlighted as orange) indicates salinity and water toxicity for drinking purpose. Sample 5 was collected from an office building that is situated amid agricultural land that grows corn and has been used for cultivation for ages which explains its high salinity and nitrate content. Since the EC sensitivity differs based on the types and age

of the plants, these waters can still be considered suitable for cultivation. However, samples 3, 4, and 5 having higher nitrate levels are not safe to drink unless treated with a reverse osmosis system. Ca^{2+} could not be tested for samples 4 and 5 as the testing equipment started giving an error in readings.

Table 3: Listing the tested results for the selected properties of water.

						Cl count	
Serial	**Water Source**	**EC (µS/cm)**	**pH**	**Ca^{2+} (ppm)**	**NO_3^- (ppm)**	**FCI (ppm)**	**TCI (ppm)**
1	AWG	31	6.53	0	0	0	0
2	Rain	91	6.94	33	10	0	0
3	Well water	764	7.45	150	15	0	0
4	Supply water	726	6.9	-	30	1	1
5	Ground water	911	7.44	-	48	0	0

3) Chlorine: The Chlorine was found only in the supply water system (highlighted blue cells), and this is expected because only the municipality water is treated with Chlorine to ensure decontamination. CDC and American Conference of Governmental Industrial Hygienists (ACGIH) restricted the safe level of free Chlorine to be 4 ppm [62] and 1 ppm [63], respectively. The amount of free Chlorine (FCl) indicates that this Chlorine is available to kill or bound with any germs or microbes that might be introduced into the water. Total Chlorine is the summation of free Chlorine and the amount of Chlorine that has already been used for disinfection for micro-organisms present in the water. Completely clean water with no contaminants shows equal TCl and FCl, which is found in the supply water sample. However, the presence of free Chlorine in the water forms Chloramine when introduced to ammonia (which is common nutrition for plants) and can hinder plant growth [13].

Conclusion: It is clear from the observation (Table 3) of the result of water quality that rainwater and AWG water have the closest values to the preferable pH range (5.5~6.5), the lowest EC with a minimal amount of minerals and no Chlorine. Having these properties as supply water for vertical farming system makes it possible to control the nutrient combination that is suitable for certain plants. Hence, the hypothesis 4 claim is accepted.

5 DESIGN FEASIBILITY: A CASE STUDY

5.1 Statement of Problem and Hypothesis

This chapter describes the design, development and assessment for hypothesis 5: *For every location and demand, an optimum RHS and AWG system size and capacity can be calculated.*

5.2 Methods and Materials

In this chapter, the following steps are taken for supply-demand calculation for the smart integrated water system in order to assess if the presently installed 3000-gallon storage tank is enough to meet the year-round demand of this particular application of vertical farming.

1) Calculation related to catchment area vs. storage capacity; water consumption vs. water supply for total of 16 tanks is performed.
2) A year-round (2019) observation is carried out to determine the seasonal demand for two farming units. Assessment is done to identify if the integrated water system meets the demand by the farming unit.
3) Detailed data are presented in plots for better observation of the water collection/generation trend by this smart integrated water system. Finally, the necessary tank size and the ratio of tank volume to catchment area are recommended.

5.3 Results

1) Total no of supply tanks = 16, the capacity of each tank = 50 gallons

   Roof catchment area for RHS is 285120 in^2 or ≈184 m^2.

   Roof length= 120'= 1440"; Width= 16.5'= 198" (Figure 16)

Tank capacity = 3000 gallons = 11.36 m^3

The present ratio of tank volume to catchment area (V/A) = 11.36/184 ≈ **0.06**.

2) Due to low atmospheric temperature and evaporation rate, the water demand is usually much lower in the winter season than in the summer. As seen in Figure 40, November, December, January, February, and March (5 months) have the average high temperature around 70° F or lower, which can be considered as winter months. Similarly, from April to October, they are considered as Summer because they have average temperatures beyond 85° F.

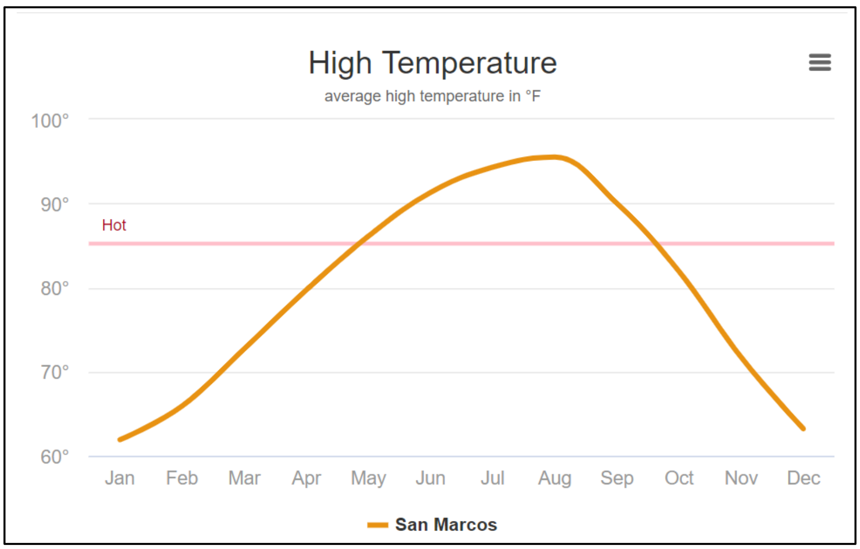

Figure 40: Average high temperature plot for San Marcos, TX [64].

3) According to collected data, each year's month-wise water generation/collection is shown in the following graphs. In 2014, the lowest production occurs in August, and about 51% of production is coming from AWG and it does not meet the minimum demand. However, rainfall of previous months is quite high. For example, May having the highest rainfall which is more than four times the maximum demand and seven times the average demand (Figure 41). In 2015, the lowest production occurs in July and August and about 31-41% of production is coming from AWG. Again, May having

a high amount of rainfall which is more than 6 times of maximum demand and 10 times of average demand (Figure 42). Similarly, in 2016 (Figure 43), the lowest production occurs in October, and about 68% of production is coming from AWG. This year, September has the highest rainfall, which is more than 4.4 times of maximum demand and 7.5 times of average demand. In 2017 (Figure 44), the lowest production occurs in July, contributing 100% of the output of that month. Again, it does not meet the minimum demand. April of this year has a large amount of rainfall, which is more than four times of maximum demand and seven times of average demand. Even September has the highest rainfall, which is more than 5.5 times of maximum demand and 9.5 times the average demand.

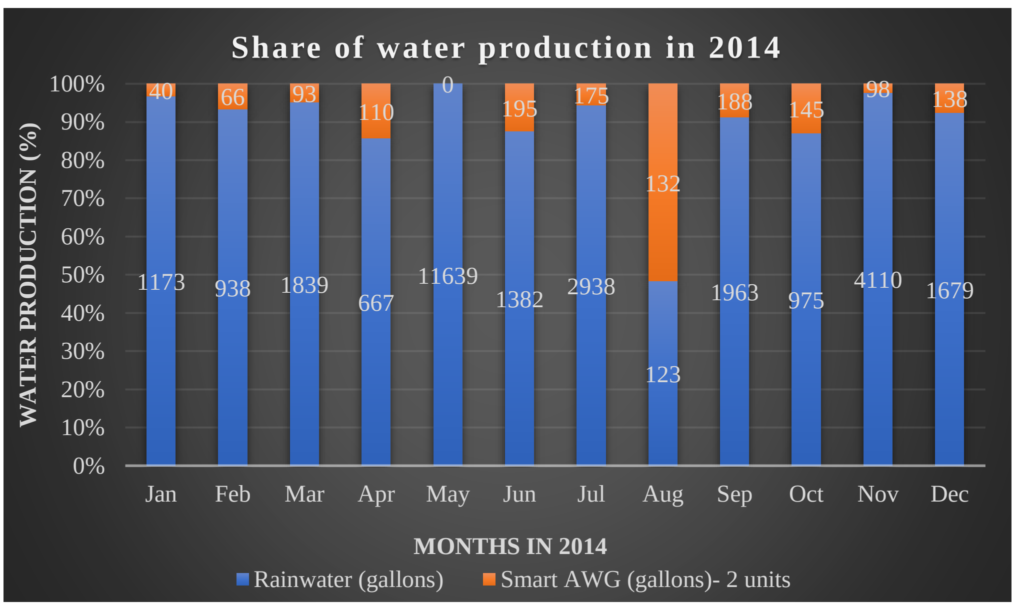

Figure 41: Share of water production in 2014 by Rain and Smart AWG.

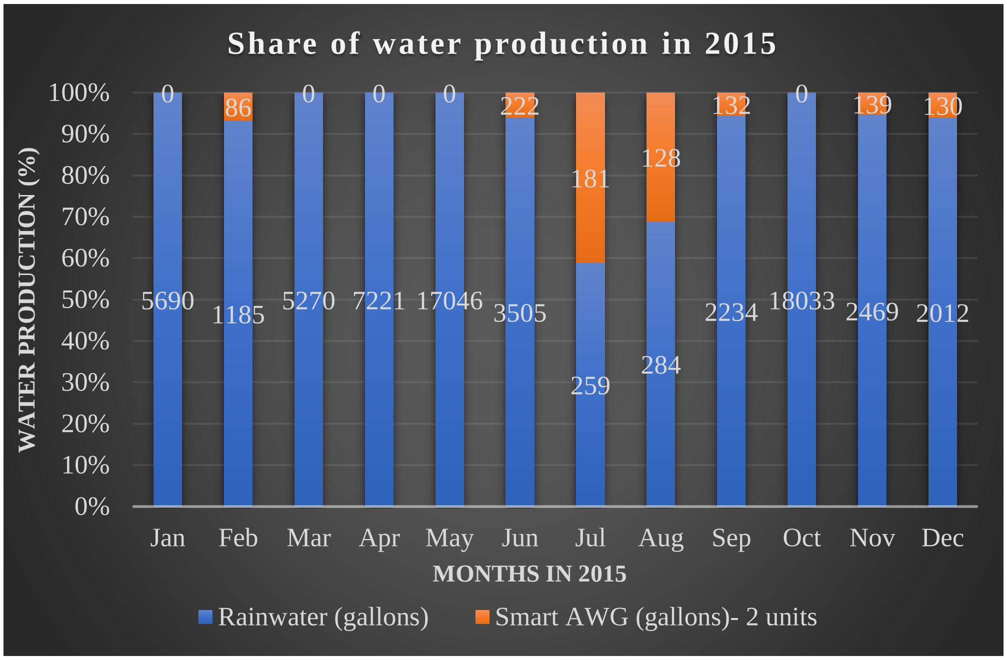

Figure 42: Share of water production in 2015 by Rain and Smart AWG.

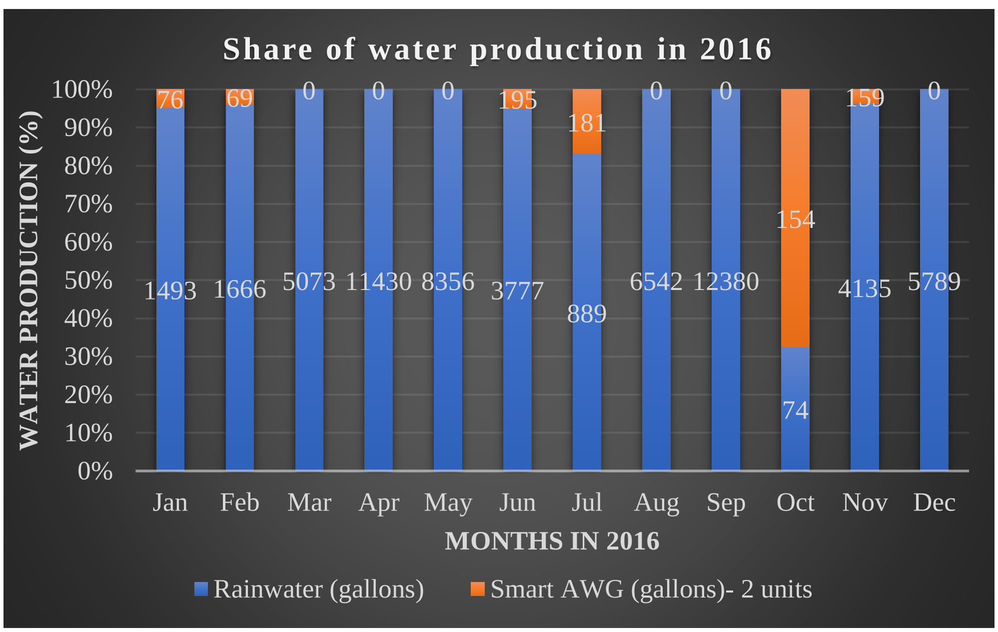

Figure 43: Share of water production in 2016 by Rain and Smart AWG.

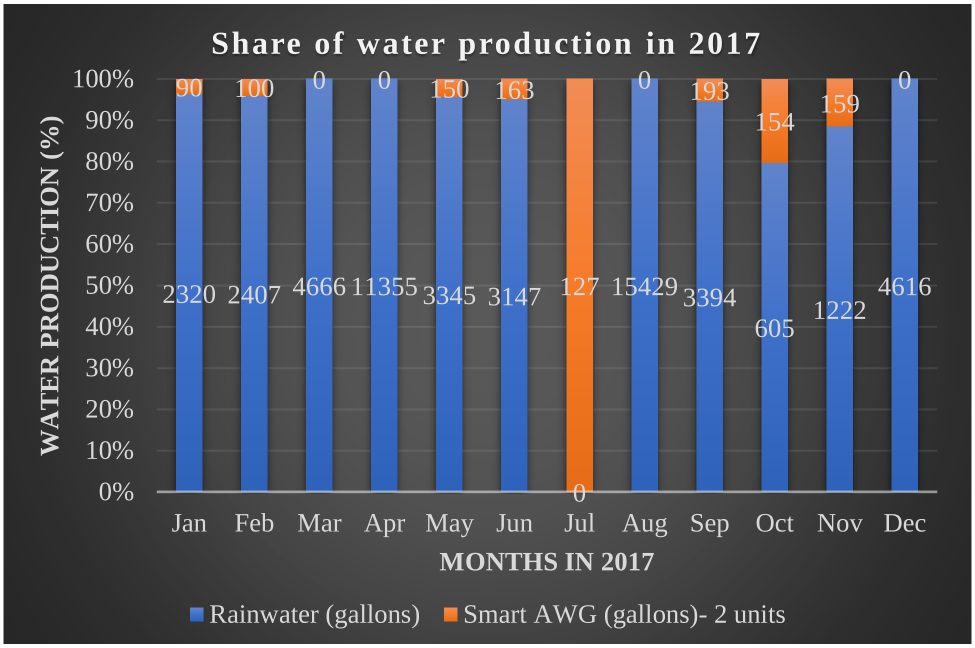

Figure 44: Share of water production in 2016 by Rain and Smart AWG.

Observations: Most of the rainfall occurs during the month of April-May and August- October which can be considered generally as summer months when the demand is also highest. But having extra reservoir capacity can provide plenty of water even in the winter months when the rainfall is very low and Smart AWG can keep producing as a back-up system.

4) Supply-demand calculation: For partial refill of the supply tanks that supply nutrition solution to vertical farming:

   a. Minimum demand, d_{min} = 64 gallons/month.

(1 gallons/week * 16 tanks*4weeks = 64 gallons/month)

Including minor cleaning and washing, system losses, and accidental spill.

   b. Maximum demand, d_{max} = 2400 gallons/month.

(5 gallons/day * 16 tanks* 30 days = 2400 gallons/month)

For full replenishment of the supply tanks in every 2 months, 800 gallons (50 gallons*16 tanks = 800 gallons) water is needed, hence,

Replenishment demand, d_R = 400 gallons/month.

Now adding these demands,

Minimum demand in total, $D_{min} = d_{min} + d_R = 64 + 400 = 464$ gallons/month

Maximum demand in total, $D_{max} = d_{max} + d_R = 2400 + 400 = 2800$ gallons/month

5) The values are tabulated to compare with the supply capacity of the integrated system in Table 4. Since a 3000-gallon tank is already installed on-site, this amount is considered available supply capacity. The achievable supply amount is calculated considering that all rainwater that falls on the catchment area (184 m^2) can be stored and hence there is no limitation for the storage tank capacity. This way the highest possible water storing capacity is found which helps to understand how much additional water storage is necessary and if that additional demand can be met.

6) In Table 4, the last column of total difference between supply and demand (S-D) is calculated considering 5 months of winter having the lowest demand (negative sign means this amount is short compared to supply) and 7 months of summer having the highest demand.

Table 4: Comparison table for the water demand of vertical farming and the supply capacity for the integrated system.

	Demand, D (gallons/month)	Supply, S (gallons/month)		Supply to demand ratio, S/D		Difference between supply & demand, (S-D)		Total (S-D)
		Available	Achievable	Available	Achievable	Available	Achievable	
Min.	464	127	127	0.27	0.27	-337	-337	-1685
Max.	2800	3000	18032	1.07	6.44	200	15232	1400
Avg.	1632	3000	4394	1.83	2.69	1368	2762	9576

This calculation yields to 1685 gallons (highlighted in orange) of water shortage from 5 months and 1400 gallons (highlighted in blue) of surplus water from the 7 months of Summer. This leads to a total year-round shortage of 245 gallons.

<u>Observations:</u> This water system will not meet the minimum demand during the winter season as the supply capacity is only 27% compared to the demand. During summer months, the water demand goes higher, but the supply capacity goes higher as well. The production can satisfactorily meet the demand during these times. On average, if there were additional tanks, 4394 gallons of water could be collected each month, which is more than 2.5 times higher than the average demand. Storing some of this excess water can be useful to make up the lack of water supply for the winter months. Hence, taking into consideration that the surplus of 1400 gallons of water during Summer can be stored and still there is a yearly shortage of 285 (1685-1400) gallons of water; adding a 2000-gallon water tank to the existing system would be enough to ensure that this system can meet consistent water demand throughout each year.

Hence, to support two units of the vertical system, considering the same catchment area (184 m^2) for RHS and two AWG units, and existing reservoir,

Revised total tank capacity = 5000 gallons = 18.93 m^3

The recommended ratio of tank volume to catchment area (V/A) = 18.93/184 ≈ **0.1**.

<u>Conclusion:</u> The results show that if the historical meteorological data is available and the water demand is known, an optimum RHS and AWG system size and capacity can be calculated for any location. Hence, hypothesis-5 claim is accepted.

6 CONCLUSION AND DISCUSSION

This smart integrated water system is developed in a way that it can be operated autonomously. As a result, this system eliminates the need of any operator who otherwise had to be always present on-site to assess the water level, analyze atmospheric condition data to detect feasibility to run the AWG and finally turn it on and off. The water generated from AWG would have to be dispatched and carried to the supply tank by someone. Since the generation stops when the AWG tanks are full of their capacity, the system would have to wait until someone empties the tanks to resume production even though the environmental condition were very favorable for water generation between these times. While the water from this integrated system proves to be very suitable for vertical farming, it might not be a good choice to use it as regular drinking water due to its lack of mineral content. However, since the water treatment is expensive and the purest water is preferred for soil-less cultivation, this smart integrated water system using RHS as a primary source, can be a better choice in terms of water quality and cost in the long run. Observing the operation of this system clarified that such an integrated system is very location dependent. Available area/rooftop for rainwater catchment, available reservoir capacity, energy price, and degree of risk that consumers can take about water shortage are among factors that may affect the scale of the system and the ratio between RHS and AWG.

7 FUTURE WORK

A more systematic approach for calculating can be framed for designing RHS size and determining the number of AWG systems based on different climate and application types. A more accurate data collection process regarding water usage can be helpful for accurate system design. A systematic cost assessment of this integrated system by including energy and water costs, investment, depreciation, and break-even point analysis can help understand the financial aspect of this research. Also, an integrated RHS-AWG-Municipal water system can be investigated to optimize cost and risk. However, utilizing more accurate technologies to offer more flexible decisions for RHS floating level; wireless technologies and cloud data collection for analyzing rain forecasting data are potential scopes to explore.

APPENDIX SECTION

APPENDIX A

Table A- 1: A sample of showing the calculation for AWG water data directly achieved in liter.

Year	Month	Day	AWG Water (Liter)	Total (2 units) AWG Water (Liter)
2014	1	7	0.00	0.00
2014	1	8	6.51	13.02
2014	1	9	11.45	22.90
2014	1	10	12.53	25.06
2014	1	11	2.52	5.04
2014	1	12	6.57	13.15
2014	1	13	1.41	2.81
2014	1	24	0.81	1.62
2014	2	25	13.10	26.20
2014	2	26	3.04	6.08
2014	2	27	1.52	3.03
2014	2	28	4.84	9.67
2014	3	1	10.75	21.49
2014	3	2	8.48	16.95
2014	3	3	0.46	0.92
2014	3	4	4.34	8.68
2014	3	5	6.54	13.08

Table A- 2: A sample of showing the calculation for converting rainfall (inch) data into the volume of collectable water (cubic-inch).

Year	Month	Day	Rain (in)	Collected Water (in^3)	Collected Water (Liters)
2014	1	7	0	0.00	0.00
2014	1	8	0.2	57024.00	934.46
2014	1	9	0.09	25660.80	420.51
2014	1	10	0	0.00	0.00
2014	1	11	0	0.00	0.00
2014	1	12	0	0.00	0.00
2014	1	13	0.4	114048.00	1868.92
2014	1	24	0.26	74131.20	1214.80
2014	2	25	0.01	2851.20	46.72
2014	2	26	0.07	19958.40	327.06
2014	2	27	0.26	74131.20	1214.80
2014	2	28	0	0.00	0.00
2014	3	1	0	0.00	0.00

2014	3	2	0	0.00	0.00
2014	3	3	0	0.00	0.00
2014	3	4	0.4	114048.00	1868.92
2014	3	5	0.5	142560.00	2336.14

Table A- 3: A sample of showing the calculation for normalizing the water generation/collection data for both water systems.

Years	Months	Rainwater, (liter)	Rainwater (normalized)	Total AWG Water (liter)	AWG Water (normalized)	Sum of Normalized Data
2014	Jan	4439	0.07	150.30	0.00	0.07
	Feb	3551	0.05	250.95	0.14	0.19
	Dec	6354	0.09	522.22	0.51	0.61
2015	Jan	21539	0.32	291.19	0.19	0.51
	May	64524	0.95	873.92	1.00	1.95
	Oct	68262	1.00	410.22	0.36	1.36
	Nov	9345	0.14	526.44	0.52	0.66
2016	Jan	5653	0.08	286.15	0.19	0.27
	Feb	6308	0.09	261.74	0.15	0.25
	Oct	280	0.00	581.40	0.60	0.60
2017	Jan	8784	0.13	339.55	0.26	0.39
	Feb	9111	0.13	380.26	0.32	0.45

Table A- 4: Precipitation data and calculated collectible rainwater amount including normalized values considering the lowest value as 0 (highlighted as orange) and the highest value as 1(highlighted as green).

Years	Months	Total Rain/Month(in)	Rainwater, A(liter)	Rainwater (gallons)	Rain (normalized)
2014	Jan	0.95	4439	1173	0.07
	Feb	0.76	3551	938	0.05
	Mar	1.49	6962	1839	0.10
	Apr	0.54	2523	667	0.04
	May	9.43	44060	11639	0.65
	Jun	1.12	5233	1382	0.08
	Jul	2.38	11120	2938	0.16
	Aug	0.1	467	123	0.01
	Sep	1.59	7429	1963	0.11
	Oct	0.79	3691	975	0.05
	Nov	3.33	15559	4110	0.23
	Dec	1.36	6354	1679	0.09
2015	Jan	4.61	21539	5690	0.32

	Feb	0.96	4485	1185	0.07
	Mar	4.27	19951	5270	0.29
	Apr	5.85	27333	7221	0.40
	May	13.81	64524	17046	0.95
	Jun	2.84	13269	3505	0.19
	Jul	0.21	981	259	0.01
	Aug	0.23	1075	284	0.02
	Sep	1.81	8457	2234	0.12
	Oct	14.61	68262	18033	1.00
	Nov	2	9345	2469	0.14
	Dec	1.63	7616	2012	0.11
2016	Jan	1.21	5653	1493	0.08
	Feb	1.35	6308	1666	0.09
	Mar	4.11	19203	5073	0.28
	Apr	9.26	43265	11430	0.63
	May	6.77	31631	8356	0.46
	Jun	3.06	14297	3777	0.21
	Jul	0.72	3364	889	0.05
	Aug	5.3	24763	6542	0.36
	Sep	10.03	46863	12380	0.69
	Oct	0.06	280	74	0.00
	Nov	3.35	15652	4135	0.23
	Dec	4.69	21913	5789	0.32
2017	Jan	1.88	8784	2320	0.13
	Feb	1.95	9111	2407	0.13
	Mar	3.78	17661	4666	0.26
	Apr	9.2	42985	11355	0.63
	May	2.71	12662	3345	0.19
	Jun	2.55	11914	3147	0.17
	Jul	0	0	0	0.00
	Aug	12.5	58404	15429	0.86
	Sep	2.75	12849	3394	0.19
	Oct	0.49	2289	605	0.03
	Nov	0.99	4626	1222	0.07
	Dec	3.74	17474	4616	0.26
		Average	16462.03	4348.81	0.24

Table A- 5: Water collection data for Atmospheric Water Generator (AWG) including normalized values for AWG considering the lowest value as 0 (highlighted as orange) and the highest value as 1 (highlighted as green). Smart AWG has no production when the rainfall amount is greater than its average value.

Years	Months	Total AWG Production-2 units (liter)	Smart AWG (liter)- 2 units	Smart AWG (gallons)- 2 units	AWG (normalized)
2014	Jan	150.30	150	40	0.00
	Feb	250.95	251	66	0.14
	Mar	352.27	352	93	0.28
	Apr	418.26	418	110	0.37
	May	515.74	0	0	0.51
	Jun	739.07	739	195	0.81
	Jul	662.10	662	175	0.71
	Aug	499.75	500	132	0.48
	Sep	712.35	712	188	0.78
	Oct	550.07	550	145	0.55
	Nov	369.37	369	98	0.30
	Dec	522.22	522	138	0.51
2015	Jan	291.19	0	0	0.19
	Feb	325.07	325	86	0.24
	Mar	568.32	0	0	0.58
	Apr	639.28	0	0	0.68
	May	873.92	0	0	1.00
	Jun	840.33	840	222	0.95
	Jul	683.64	684	181	0.74
	Aug	484.21	484	128	0.46
	Sep	500.09	500	132	0.48
	Oct	410.22	0	0	0.36
	Nov	526.44	526	139	0.52
	Dec	490.32	490	130	0.47
2016	Jan	286.15	286	76	0.19
	Feb	261.74	262	69	0.15
	Mar	491.76	0	0	0.47
	Apr	577.91	0	0	0.59
	May	784.25	0	0	0.88
	Jun	736.36	736	195	0.81
	Jul	683.58	684	181	0.74
	Aug	865.69	0	0	0.99
	Sep	730.16	0	0	0.80
	Oct	581.40	581	154	0.60
	Nov	600.74	601	159	0.62
	Dec	456.33	0	0	0.42
2017	Jan	339.55	340	90	0.26
	Feb	380.26	380	100	0.32
	Mar	507.29	0	0	0.49

	Apr	535.32	0	0	0.53
	May	569.54	570	150	0.58
	Jun	616.44	616	163	0.64
	Jul	479.75	480	127	0.46
	Aug	865.69	0	0	0.99
	Sep	730.16	730	193	0.80
	Oct	581.40	581	154	0.60
	Nov	600.74	601	159	0.62
	Dec	456.33	0	0	0.42
	Average	543.63	344.26	90.94	0.54

APPENDIX B

Table B-1: Full algorithm for the generation side automation written in Arduino software.

```
//title: "Generation Code"
//author: "Fatema Tuz Zohra"
//date: "6/15/2020"
// Example sketch for DHT22 humidity - temperature sensor
//thanks to Adafruit for bits of their library. public domain
#include "cactus_io_DHT22.h"
#include <stdint.h>
#define DHT22_PIN 2     // DHT22 connection pin
#define FLOAT_SENSOR  7   // float switch digital IO connection pin2
#define pump_1    8      // water pump digital IO connection pin7
DHT22 dht(DHT22_PIN);
void setup() {
  Serial.begin(9600);
  Serial.println("DHT22 Humidity - Temperature Sensor");
  Serial.println("RH\t\tTemp (C)\tTemp (F)\tHeat Index (C)\t Heat Index (F)");
  pinMode(13,OUTPUT);
  pinMode(pump_1, OUTPUT);
  // initialize the float switch pin as a pullup input
  pinMode(FLOAT_SENSOR, INPUT_PULLUP);
  dht.begin();
}
void loop() {
  dht.readHumidity();
  dht.readTemperature();
   // Check if any reads failed and exit early (to try again).
  if (isnan(dht.humidity) || isnan(dht.temperature_C)) {
    Serial.println("DHT sensor read failure!");
    return;
  }
  Serial.print(dht.humidity); Serial.print(" %\t\t");
  Serial.print(dht.temperature_F); Serial.print(" *F\t");
//Ranges of relative humidity and temperature are defined
  if(dht.humidity>30.00 && dht.humidity<100.00){
    if (dht.temperature_F>55.00 && dht.temperature_F<120.00){
    digitalWrite(13, HIGH); //Turn on AWG
     }
  }
  else{
    digitalWrite(13, LOW); //Turn OFF AWG
  }
//controlling the pump by the float
   if(digitalRead(FLOAT_SENSOR) == HIGH)//water level is up
  {
    //Serial.print("Water level is up");
    digitalWrite(pump_1, HIGH);// start the pump
    delay(20*60*1000UL); //pump stays on for 20 min
      }
  if(digitalRead(FLOAT_SENSOR) == LOW)//water level is up
  {
    digitalWrite(pump_1, LOW);// start the pump
      }  }
```

Table B-2: Full algorithm for the delivery side automation written in Arduino software.

```
//title: "Consumption Code"
//author: "Fatema Tuz Zohra"
//date: "6/15/2020"

// Sketch for float-solenoid control

#include <stdint.h>
// float switch digital connection pins
#define FLOAT_1     2
#define FLOAT_2     4
#define FLOAT_3     6
#define FLOAT_4     7

// solenoids digital connection pins
#define solenoid_1     13
#define solenoid_2     12
#define solenoid_3     11
#define solenoid_4     10


void setup ()
{
  Serial.begin(115200);
  // solenoid as output
  pinMode(solenoid_1, OUTPUT);
   pinMode(solenoid_2, OUTPUT);
     pinMode(solenoid_3, OUTPUT);
   pinMode(solenoid_4, OUTPUT);

  // top floats as a pullup input
  pinMode(FLOAT_1, INPUT_PULLUP);
    pinMode(FLOAT_2, INPUT_PULLUP);
      pinMode(FLOAT_3, INPUT_PULLUP);
    pinMode(FLOAT_4, INPUT_PULLUP);

}

void loop()
{
  //Assessing Tank water level simultaneously for all the four tanks


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  LOW)
  { digitalWrite(solenoid_1,  LOW );
   digitalWrite(solenoid_2,  LOW );
   digitalWrite(solenoid_3,  LOW );
   digitalWrite(solenoid_4,  LOW );
   delay(5*60*1000UL);} //solenoid stays open for 5 minutes


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  HIGH)
  { digitalWrite(solenoid_1,  LOW );
```

```
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  HIGH );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  HIGH)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  HIGH );
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  HIGH)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  HIGH );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  LOW  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  HIGH)
 { digitalWrite(solenoid_1,  LOW );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  HIGH );
```

```
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  HIGH)
 {  digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  HIGH );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  LOW  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  HIGH)
 { digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  LOW );
  digitalWrite(solenoid_3,  HIGH );
  digitalWrite(solenoid_4,  HIGH );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  LOW)
 { digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  LOW );
  delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  LOW  && digitalRead(FLOAT_4) ==  HIGH)

  {digitalWrite(solenoid_1,  HIGH );
  digitalWrite(solenoid_2,  HIGH );
  digitalWrite(solenoid_3,  LOW );
  digitalWrite(solenoid_4,  HIGH );
```

```
   delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  LOW)
   {digitalWrite(solenoid_1,  HIGH );
   digitalWrite(solenoid_2,  HIGH );
   digitalWrite(solenoid_3,  HIGH );
   digitalWrite(solenoid_4,  LOW );
   delay(5*60*1000UL);}


if(digitalRead(FLOAT_1) ==  HIGH  && digitalRead(FLOAT_2) ==  HIGH  &&
digitalRead(FLOAT_3) ==  HIGH  && digitalRead(FLOAT_4) ==  HIGH)
 {  digitalWrite(solenoid_1,  HIGH );
   digitalWrite(solenoid_2,  HIGH );
   digitalWrite(solenoid_3,  HIGH );
   digitalWrite(solenoid_4,  HIGH );
 }
}
```

REFERENCES

[1] M. Hameed, P. Abbaszadeh, A. Ahmadalipour, A. Alipour, H. Moftakhari, and H. Moradkhani, "A Review of the 21st Century Challenges in the Food-Energy-Water Security in the Middle East," *Water*, vol. 11, no. 4, Apr. 2019.

[2] D. J. Garcia and F. You, "The water-energy-food nexus and process systems engineering: A new focus," *Comput. Chem. Eng.*, vol. 91, pp. 49–67, 2016.

[3] L. Swatuk, M. McMorris, C. Leung, and Y. Zu, "Seeing 'invisible water': Challenging conceptions of water for agriculture, food and human security," *Can. J. Dev. Stud.*, vol. 36, no. 1, pp. 24–37, 2015.

[4] "Chart: Globally, 70% of Freshwater is Used for Agriculture." [Online]. Available: http://blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture. [Accessed: 01-Jan-2020].

[5] P. Pingmuanglek, N. Jakrawatana, and S. H. Gheewala, "Freshwater use analysis of cassava for food feed fuel in the Mun River basin, Thailand," *Int. J. Life Cycle Assess.*, vol. 22, no. 11, pp. 1705–1717, 2017.

[6] R. Kaewmai, T. Grant, S. Eady, J. Mungkalasiri, and C. Musikavong, "Improving regional water scarcity footprint characterization factors of an available water remaining (AWARE)method," *Sci. Total Environ.*, vol. 681, pp. 444–455, 2019.

[7] J. He, "Farming of Vegetables in Space-Limited Environments," *Cosmos*, vol. 11, no. 01, pp. 21–36, 2015.

[8] H. S. Grewal, B. Maheshwari, and S. E. Parks, "Water and nutrient use efficiency of a low-cost hydroponic greenhouse for a cucumber crop: An Australian case study," *Agric. Water Manag.*, vol. 98, no. 5, pp. 841–846, 2011.

[9] "Is Hydroponic Plantation Beneficial? | Everchem Fertilizer Company." [Online]. Available: https://everchem.com.my/is-hydroponic-plantation-beneficial/. [Accessed: 29-May-2020].

[10] J. Birkby, "Vertical Farming," *Natl. Cent. Appropr. Technol.*, vol. 88, no. 12, pp. 1173–1176, 2016.

[11] J. J. A. Dominguez, C. Inoue, and M.-F. Chien, "Hydroponic approach to assess rhizodegradation by sudangrass (Sorghum x drummondii) reveals pH- and plant age-dependent variability in bacterial degradation of polycyclic aromatic hydrocarbons (PAHs)," *J. Hazard. Mater.*, p. 121695, 2019.

[12] "Water Treatment | Public Water Systems | Drinking Water | Healthy Water | CDC." [Online]. Available: https://www.cdc.gov/healthywater/drinking/public/water_treatment.html. [Accessed: 28-May-2020].

[13] "Using Tap Water For Hydroponics | Green and Vibrant." [Online]. Available: https://www.greenandvibrant.com/tap-water-hydroponics. [Accessed: 28-May-2020].

[14] "EverGreen : Texas State University." [Online]. Available: https://www.evergreen.txstate.edu/. [Accessed: 14-Jun-2020].

[15] S. R. Ghimire and J. M. Johnston, "Traditional Knowledge of Rainwater Harvesting Compared to Five Modern Case Studies," in *World Environmental and Water Resources Congress 2015*, 2015, pp. 182–193.

[16] B. Asiabanpour, N. Ownby, M. Summers, and F. Moghimi, “Atmospheric water generation and energy consumption: An empirical analysis,” in *2019 IEEE Texas Power and Energy Conference, TPEC 2019*, 2019.

[17] “Rainwater Harvesting | Napa Water Containment Services, Fire Protection Tanks and Rain Water Harvesting Tanks.” [Online]. Available: https://watermarkh2o.com/general-information/rainwater-harvesting/. [Accessed: 27-Dec-2019].

[18] “Pinterest.” [Online]. Available: https://www.pinterest.nz/pin/368802656966633499/. [Accessed: 27-Dec-2019].

[19] B. Gido, E. Friedler, and D. M. Broday, “Assessment of atmospheric moisture harvesting by direct cooling,” *Atmos. Res.*, vol. 182, pp. 156–162, Dec. 2016.

[20] M. P. Jones and W. F. Hunt, “Performance of rainwater harvesting systems in the southeastern United States,” *Resour. Conserv. Recycl.*, vol. 54, no. 10, pp. 623–629, 2010.

[21] S. Ward, F. A. Memon, and D. Butler, “Performance of a large building rainwater harvesting system,” *Water Res.*, vol. 46, no. 16, pp. 5127–5134, Oct. 2012.

[22] N. H. M. Lani, A. Syafiuddin, Z. Yusop, U. binti Adam, and M. Z. bin M. Amin, “Performance of small and large scales rainwater harvesting systems in commercial buildings under different reliability and future water tariff scenarios,” *Sci. Total Environ.*, vol. 636, pp. 1171–1179, 2018.

[23] K. Tamaddun, A. Kalra, and S. Ahmad, “Potential of rooftop rainwater harvesting to meet outdoor water demand in arid regions,” *J. Arid Land*, vol. 10, no. 1, pp. 68–83, 2018.

[24] "NADP Animated Maps." [Online]. Available: http://nadp.slh.wisc.edu/data/animaps.aspx. [Accessed: 28-May-2020].

[25] C. R. Fonseca, V. Hidalgo, C. Díaz-Delgado, A. Y. Vilchis-Francés, and I. Gallego, "Design of optimal tank size for rainwater harvesting systems through use of a web application and geo-referenced rainfall patterns," *J. Clean. Prod.*, vol. 145, pp. 323–335, Mar. 2017.

[26] F. T. Malik, R. M. Clement, D. T. Gethin, W. Krawszik, and A. R. Parker, "Nature's moisture harvesters: A comparative review," *Bioinspiration and Biomimetics*, vol. 9, no. 3. Institute of Physics Publishing, 2014.

[27] T. Nørgaard and M. Dacke, "Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles," *Front. Zool.*, vol. 7, no. 1, p. 23, 2010.

[28] "Could this desert beetle help humans harvest water from thin air? | Science | AAAS." [Online]. Available: https://www.sciencemag.org/news/2019/11/could-desert-beetle-help-humans-harvest-water-thin-air. [Accessed: 29-Dec-2019].

[29] "Leaves channel dew as water source : Welwitschia - AskNature." [Online]. Available: https://asknature.org/strategy/leaves-channel-dew-as-water-source/. [Accessed: 29-Dec-2019].

[30] "Web directs continuous water collection : Uloborus walckenaerius - AskNature." [Online]. Available: https://asknature.org/strategy/web-directs-continuous-water-collection/#.XghSIEdKg2w. [Accessed: 29-Dec-2019].

[31] "Desert Frogs 'Fog Up' to Collect Water | Live Science." [Online]. Available: https://www.livescience.com/16325-desert-frogs-collect-water.html. [Accessed: 29-Dec-2019].

[32] Z. Almusaied and B. Asiabanpour, “Atmospheric Water Generation: Technologies and Influential Factors Abstract ID: 2914.”

[33] G. M. Peters, N. J. Blackburn, and M. Armedion, “Environmental assessment of air to water machines - Triangulation to manage scope uncertainty,” *Int. J. Life Cycle Assess.*, vol. 18, no. 5, pp. 1149–1157, Jun. 2013.

[34] C. Anand and D. S. Apul, “Economic and environmental analysis of standard, high efficiency, rainwater flushed, and composting toilets,” *J. Environ. Manage.*, vol. 92, no. 3, pp. 419–428, Mar. 2011.

[35] X. Yan, S. Ward, D. Butler, and B. Daly, “Performance assessment and life cycle analysis of potable water production from harvested rainwater by a decentralized system,” *J. Clean. Prod.*, vol. 172, pp. 2167–2173, 2018.

[36] I. Lekouch, M. Muselli, B. Kabbachi, J. Ouazzani, I. Melnytchouk-Milimouk, and D. Beysens, “Dew, fog, and rain as supplementary sources of water in south-western Morocco,” *Energy*, vol. 36, no. 4, pp. 2257–2265, 2011.

[37] S. S. Lagu and S. B. Deshmukh, “Raspberry Pi for automation of water treatment plant,” *2014 International Conference on Advances in Computing, Communications and Informatics (ICACCI), Advances in Computing, Communications and Informatics (ICACCI, 2014 International Conference on*. IEEE, pp. 1999–2003, 01-Sep-2014.

[38] J. Tomlinson, E. Johnson, C. Chesser 4, and J. Moore 6, “automated water filtration system design challenge.,” *Technol. Eng. Teach.*, vol. 79, no. 4, pp. 32–36, Dec. 2019.

[39] B. I. Farhan, “Design and Construct Intelligent Tank ‘Water Level Sensor’.,” *J. AL-Qadisiyah Comput. Sci. Math.*, vol. 10, no. 3, pp. 1–8, Sep. 2018.

[40] E. C. Prima, S. S. Munifaha, R. Salam, M. H. Aziz, and A. T. Suryani, “Automatic Water Tank Filling System Controlled Using ArduinoTM Based Sensor for Home Application,” *Procedia Eng.*, vol. 170, no. Engineering Physics International Conference 2016-EPIC 2016, pp. 373–377, Jan. 2017.

[41] H. Ahmad and U. Atikol, “A simple algorithm for reducing the operation frequency of residential water pumps during peak hours of power consumption.,” *Energy Sci. Eng.*, vol. 6, no. 4, pp. 253–271, Aug. 2018.

[42] Z. Yuan *et al.*, “Sweating the assets - The role of instrumentation, control and automation in urban water systems,” *Water Research*, vol. 155. pp. 381–402.

[43] P. Gaonkar and M. Kande, “Challenges and opportunities of automation system for water and waste water applications,” *2014 IEEE International Conference on Industrial Technology (ICIT), Industrial Technology (ICIT), 2014 IEEE International Conference on*. IEEE, pp. 682–688, 01-Feb-2014.

[44] T. Imanaliyev tonimontana, O. Karlykhanov, M. Li, N. Bakbergenov, A. Zhakashov, and D. Ponkratyev, “Automation of water facilities in Kazakhstan and its solutions.,” *Contemp. Dilemmas Mag. Educ. Polit. Values*, vol. 7, no. 1, pp. 1–30, Sep. 2019.

[45] M. Li, O. Karlykhanov, D. Ponkratyev, T. Imanaliyev, and T. Tazhiyeva, “Automatic water meter for gauging stations of irrigation canals,” *SPACES Mag.*, vol. 39, no. 34, Aug. 2018.

[46] “Hydroponics: A Standard Methodology for Plant Biological Researches - Google Books.” [Online]. Available: https://books.google.com/books?hl=en&lr=&id=otCcDwAAQBAJ&oi=fnd&pg=PA1&dq=%22EC%22+or+%22hydroponic%22+and+%22water+quality%22&ots=BeDdLCb30U&sig=EfWw5vcRLAjOhGo5L-GsF36fmgI#v=onepage&q&f=false. [Accessed: 27-May-2020].

[47] “Understanding Water Quality, Water EC, and pH Grace AEssense Applications Scientist,” 2016.

[48] S. Date, S. Terabayashi, Y. Kobayashi, and Y. Fujime, “Effects of chloramines concentration in nutrient solution and exposure time on plant growth in hydroponically cultured lettuce,” *Sci. Hortic. (Amsterdam).*, vol. 103, no. 3, pp. 257–265, 2005.

[49] O. Burgara-Montero, J. M. Ponce-Ortega, M. Serna-González, and M. M. El-Halwagi, “Optimal design of distributed treatment systems for the effluents discharged to the rivers,” *Clean Technol. Environ. Policy*, vol. 14, no. 5, pp. 925–942, Oct. 2012.

[50] C. Deng, X. Feng, and Z. Wen, “Optimization of water network integrated with process models,” *Clean Technol. Environ. Policy*, vol. 15, no. 3, pp. 473–487, Jun. 2013.

[51] S. G. Youn, E. S. Chung, W. G. Kang, and J. H. Sung, “Probabilistic estimation of the storage capacity of a rainwater harvesting system considering climate change,” *Resour. Conserv. Recycl.*, vol. 65, pp. 136–144, Aug. 2012.

[52] C. S. Khor, B. Chachuat, and N. Shah, “A superstructure optimization approach for water network synthesis with membrane separation-based regenerators,” *Comput. Chem. Eng.*, vol. 42, pp. 48–63, Jul. 2012.

[53] E. Rubio-Castro, J. M. Ponce-Ortega, F. Nápoles-Rivera, M. M. El-Halwagi, M. Serna-González, and A. Jiménez-Gutiérrez, “Water integration of eco-industrial parks using a global optimization approach,” *Ind. Eng. Chem. Res.*, vol. 49, no. 20, pp. 9945–9960, Oct. 2010.

[54] C. Sotelo-Pichardo, J. M. Ponce-Ortega, M. M. El-Halwagi, and S. Frausto-Hernández, “Optimal retrofit of water conservation networks,” *J. Clean. Prod.*, vol. 19, no. 14, pp. 1560–1581, Sep. 2011.

[55] J. S. Mun and M. Y. Han, “Design and operational parameters of a rooftop rainwater harvesting system: Definition, sensitivity and verification,” *J. Environ. Manage.*, vol. 93, no. 1, pp. 147–153, 2012.

[56] “Normalized Data / Normalization - Statistics How To.” [Online]. Available: https://www.statisticshowto.com/normalized/. [Accessed: 14-Jun-2020].

[57] “AWS - Home.” [Online]. Available: https://www.atmosphericwatersolutions.com/. [Accessed: 29-Dec-2019].

[58] I. Atmospheric Water Solutions, “Manual_AquaboyPro.II,” *Natl. Energy Distrib. Co.*, 1392.

[59] “Pocket Meters - LAQUA [Water Quality Analyzer Website] - HORIBA.” [Online]. Available: https://www.horiba.com/uk/application/material-property-characterization/water-analysis/water-quality-electrochemistry-instrumentation/compact/. [Accessed: 14-Jun-2020].

[60] “Insta-Test Free and Total Chlorine Test Strips - 3027.” [Online]. Available: https://lamotte.com/insta-test-free-and-total-chlorine-test-strips. [Accessed: 14-Jun-2020].

[61] U. of A. S. Division of Agriculture, “Interpretation of Water Testing Results Domestic Package.” [Online]. Available: https://www.uaex.edu/counties/craighead/Interpretation%20of%20Water%20Testing%20Results%20domestic.pdf. [Accessed: 10-June-2020].

[62] “Disinfection with Chlorine | Public Water Systems | Drinking Water | Healthy Water | CDC.” [Online]. Available: https://www.cdc.gov/healthywater/drinking/public/chlorine-disinfection.html. [Accessed: 10-Jun-2020].

[63] S. Arsawiset and S. Teepoo, “Analytica Chimica Acta Ready-to-use , functionalized paper test strip used with a smartphone for the simultaneous on-site detection of free chlorine , hydrogen sul fi de and formaldehyde in wastewater,” *Anal. Chim. Acta*, vol. 1118, pp. 63–72, 2020.

[64] “San Marcos, Texas Climate.” [Online]. Available: https://www.bestplaces.net/climate/city/texas/san_marcos. [Accessed: 31-May-2020].