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Efficiency Mapping and Determination of Reliability, Resiliency and Vulnerability of Atmospheric Water Generators in the United States

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EFFICIENCY MAPPING AND DETERMINATION OF RELIABILITY, RESILIENCY AND VULNERABILITY OF ATMOSPHERIC WATER GENERATORS IN THE UNITED STATES

THESIS

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Abstract

Atmospheric Water Generators (AWG) extract water from the air using one of three available technologies: refrigeration, sorption, and fog harvesting. A refrigeration device works like a dehumidifier and works best in conditions above 60% relative humidity. A sorption device utilizes a desiccant to extract the water vapor from the air and works in very low humidity levels. A fog harvesting device utilizes a mesh to capture the water vapor from the air and requires 100% relative humidity. In this research, I analyze two refrigeration-based devices and one sorption-based device and their efficacy in providing supplemental water supply. An AWG can supply potable water to remote and austere locations where clean drinking water might otherwise be unavailable. With the increase in water scarcity on the global stage, new methods that can draw from an estimated 141.9E16 liters in the atmosphere using an AWG becomes important and, potentially, viable. However, due to climatological and technological constraints, not all regions in the world would see the same water production from an AWG as production is driven by high relative humidity and temperature. This climatological reliance also subjects them to dramatic changes in performance depending on the season. By using previously established hydrologic performance indicators and weather data for the United States, I determine the year-round efficiency metrics of the typical residential-sized refrigeration AWG. Using these efficiency metrics, I also determined the reliability, resiliency, and vulnerability of the AWG to produce potable water seasonally across the United States. By evaluating several different devices and mapping the efficiency on the country-scale, this research determines the regional efficacy in adopting AWG technology to supplement potable water supply. This study

was the first to look at the performance of atmospheric water generators with such granularity, as well as comparing specific devices predicted water production output to each other and over the years and calculating their Hashimoto's hydrological indicators.

Acknowledgments

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Erica F. Sadowski

Table of Contents

List of Figures

List of Tables

EFFICIENCY MAPPING AND DETERMINATION OF RELIABILITY, RESILIENCY AND VULNERABILITY OF ATMOSPHERIC WATER GENERATORS IN THE UNITED STATES

I. Introduction

1.1 General Issue

Water is needed by every human for basic survival as well as hygiene. In many countries water is a very scarce resource. This can be due to the rural communities being far away from the more urban water sources, lack of government planning or lack of access to water [1]. An estimated 4 billion people face water scarcity at least one month in a year [2]. With water becoming increasingly scarce due to population increase and climate change, new technology that can provide potable water where it previously was not available is more important than ever. Atmospheric Water Generators (AWG) use one of three different methods to generate potable water from the air: fog harvesting, active refrigeration, and sorption [3]. Fog harvesting uses a mesh device to increase water condensation and requires 100% relative humidity [3]. Sorption uses a desiccant to separate the water vapor from the air, this method can be used in relative humidity levels as low as 20% [3]. The final method, and the most commercials used, is active refrigeration. A device that uses active refrigeration forces atmospheric water to condensate by cooling the air below the dew point temperature, this is the same process as a dehumidifier except an AWG also makes the water potable [4].

The atmosphere is filled with an estimated 12,800 trillion liters of water [4]. Conventional water sources are not always available, but the atmosphere always is. It makes it important to investigate this technology to potentially solve water scarcity in areas where other sources of water are not available. An AWG can also be combined with solar power generation making it a completely standalone system [1]. This research helps investigate the feasibility of the utility and reliability of AWG for potable water in the United States. The final product will lead a larger investigation that will determine the feasibility of using AWG at forward operating bases (FOB) and as a supplementary water supply in the event of natural disasters.

1.2 Problem Statement

How does Atmospheric Water Generator technology perform in the United States during the different seasons and how do different technologies compare? In remote locations or FOBs the Air Force relies on mobile ROWPU devices to provide potable water to their troops. Would AWGs perform better than ROWPU for the Air Force and other DoD organizations?

1.3 Research Objectives

The objective of this research was to create a model of the three selected AWG device's efficiencies utilizing GIS. This analysis shows what areas in the United States are most feasible for this technology's implementation. The model includes seasonal variations to show how efficient and reliable the devices are throughout the year.

I will create a GIS model of devices' efficiency and use the three different hydrological indicators to measure their performance utilizing 2019 weather data. The three hydrological indicators I will use are reliability, vulnerability, and resiliency as defined by Hashimoto [5]. Efficiency of a device is calculated by taking the output of the device at a given point and dividing it by the maximum device output per day. Reliability shows how often the device is in a successful state. Resiliency shows the probability of the device rebounding after a day of failure, defined as an efficiency percentage under 30. Vulnerability is defined as the daily maximum average liters of water deficiency from the failure threshold. Case study locations were chosen to showcase the results of these metrics for each device across all seasons. Additionally, the efficiency, reliability and resiliency of each device was investigated from 1985 – 2019 at the case study locations to investigate any discernible trends over time.

The technology for Atmospheric Water Generators has been available for several years, however, an investigation into their spatial and temporal performance in the United States has not been completed. Our research investigates three different AWGs using both an efficiency percentage and Hashimoto's three hydrologic indicators to compare their performances not only across the United States but also across time.

1.4 Implications

This research will explain the feasibility of AWG technology based on seasonal changes and varying climates. This data can also help show the technologies stability, or lack thereof, in areas where there are large seasonal changes. The devices chosen for this study are all mobile units, and they do not require any existing water infrastructure. This can be especially useful in rural and austere locations where there likely is not an existing water system. Often during the startup of FOBs bottled water is the only viable source of water. This is both expensive and not good for the environment. This research will aid in determining if using a type of AWG would be a feasible alternative to bottled water when a ROWPU is not viable.

II. Literature Review

2.1 Remote Water Purification Technology

In some areas the AWG can complement existing technologies such as ceramic pots. Ceramic pots are used in some remote locations, they are porous and take out most of the impurities that can be found in water; ceramic pots imbedded with silver are even more effective [6]. Another common system used in rural environments is a reverse osmosis (RO) system, however in small communities these systems can be poorly managed or have a lack of resources leading to pollutants being in the treated water [7]. With a reverse osmosis system also comes brine that requires proper disposal, at as much as a 1 to 1 ratio with usable water. This brine can have negative effects on the environment and surrounding wildlife depending on its properties. There has been research into creating more efficient RO systems such as one that recirculates water however at this point, they are still very impractical and expensive [8]. In some rural areas rainwater is captured to use as drinking water however this water still needs to be treated after being collected and it is heavily reliant on the weather [9]. Some areas in New Zealand utilize rainwater collections systems as their primary source of water and have a point of use filtration system. However, when a drought occurs this leads to a lack of water and the filtration system is not robust enough to make the water drinkable, so a separate water source must be used.

While atmospheric water harvesting technology has existed for over 20 years it has not been implemented on a large scale unlike some of the previously mentioned filtration systems [10].

This is largely in part to its current inefficiency and scalability concerns. In general, an atmospheric water generator system must meet a few criteria to be considered a viable solution, some of those include, affordable, scalable, and stable enough to provide a steady water amount year-round [10]. Based on the different technologies' reliability on the weather it seems the "year-round" criteria listed is the most difficult to meet. There are three different methods that AWGs can operate on, fog harvesting, sorption, and refrigeration. These methods are described in the following subsections.

2.1.1 Fog Harvesting

Fog harvesting typically utilizes a mesh device and requires 100% relative humidity to function [3]. The mesh is faced perpendicular to the predominant wind direction and, when the environment is foggy, the mesh traps the water droplets as the wind carries them [10]. The biggest issues with this method are its reliance on high humidity and the mesh's tendency to get clogged [10].

One example of use of this type of system are the cloud catchers in Lima, Peru. Their systems consist of 60 nets, each collecting around 200-300 liters of water per day providing water to around 250 families for free [11]. While these systems are not generally used for potable water, they are often used for agricultural purposes [11].

2.1.2 Sorption

The sorption method of atmospheric water harvesting utilizes a desiccant to separate the water vapor from the air [3]. This technology can be used in very low relative humidity levels and is typically used with solar energy. Therefore, it can function completely off the grid and is usually very mobile. However, the tradeoff for this mobility is that, out of the three methods, a single sorption based unit produces a much smaller quantity of water.

Li et al (2018) sorbent technology they created is in a form of hydrogel with deliquescent salt (i.e., $CaCl_2$ in this work) embedded inside the hydrogel and the salt is responsible for atmospheric water vapor harvesting. The unit adsorbs water at night when the temperatures are lower and humidity is higher, and water is released from the hydrogel during the day using only solar energy [3].

2.1.3 Refrigeration

The most common method used for larger scale water supply needs is active refrigeration. It is typically deemed infeasible to utilize this method in environments that experience, on average, less than 40% relative humidity. This method also has a significant energy demand to function compared to the other two methods [3]. The refrigeration method works the same as a dehumidifier with the addition of an air filter and typically a treatment method after the water is collected [3]. In two different studies by Joshi et al [12] and Shourideh et al [1] the refrigeration method was evaluated based on the water production rate relative to environmental factors [12 &

1]. Those variables are the air flow velocity, the relative humidity, and the power supply, this shows that these are the focus areas when trying to improve the technology. Both studies found that by increasing the air flow the water yield can be increased and the higher the relative humidity the higher the water yield comparing at the same temperature. The draw back of increasing the air flow however is that it greatly increases the energy demand [12]. Two devices selected for this study use this method.

2.2 Devices Selected for the Study

The three devices selected for this study range in both maximum capacity as well as efficiency. The first device (SOURCE) utilizes the sorption method chosen due to its capacity to work without an electricity source because it has an integrated solar panel. The other two devices, Tsunami, and the residential device, use refrigeration the most common method for commercially available devices. These two devices were selected based on their available data and their varying sized capacity.

2.2.1 SOURCE

The following information in this section is from the SOURCE website and their tech sheet [13]. The SOURCE water panel collects water vapor from the air onto a hygroscopic material, then with the heat from the sun it converts the water vapor into a liquid. This water is stored in the panel itself until it is collected for use. Sensors in the panel monitor the water to maintain its quality.

A single panel is 4’ x8’ x 3’8” and weighs around 340 lbs. Its optimum operating conditions are from 1 to 55 degrees Celsius and from 10 to 100% relative humidity. Each panel can produce between 2 to 5 liters of water per day.

These panels can be mounted on a roof or on the ground and be used as a standalone system or can be connected to provide water straight to the facet. The amount of water supply can be scaled up by adding more panels to the system. Figure 1 shows the relationship between the relative humidity, solar energy, and the production of water per panel per day as well as a picture of the device. When placed in an array each panel needs to have at least 1.2 meters of space in front and behind, but it can be placed right next to each other on the sides.

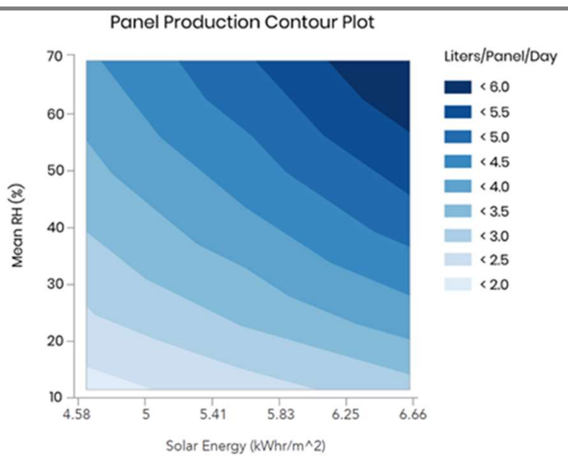
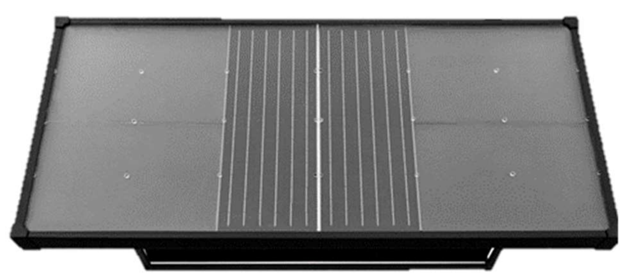
Source Water Panel Production Chart	Picture of the Source Water Panel
	

Figure 1 - SOURCE Water Panel Picture and Water Production Chart [13]

2.2.2 Tsunami

The following information on the Tsunami AWG device was gathered from their website and from talking with their representatives. Water is pulled into the Tsunami unit using fans across a multi-layer filter that removes different airborne particles such as dust and pollen. The air is then forced through condensing coils (these work the same as those you would find in a dehumidifier) forcing the moisture in the air to form water droplets. This water is collected and purified through a filtration system removing any possible pollutants. Figure 2 shows this process.

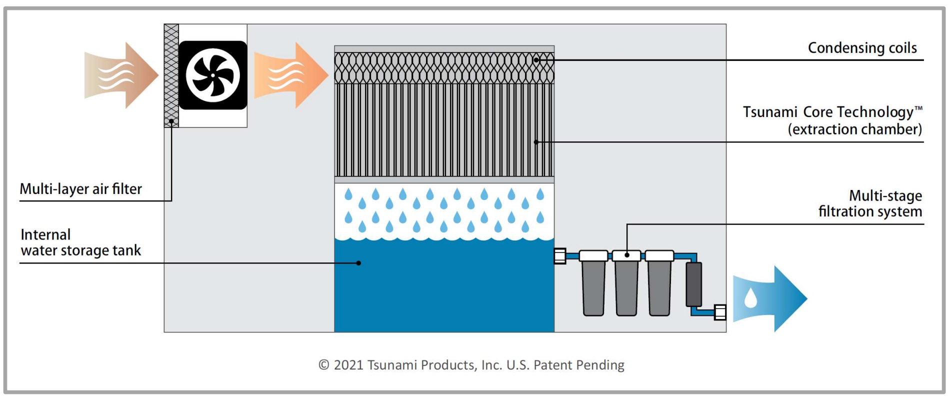


Figure 2 - Tsunami Device Water Extraction Process [14]

The Tsunami company has several different sized devices, the one utilized in this research is the Tsunami-500 it is 42”x42”x90” and weighs 850 lbs. This device can produce up to 773 liters of water per day but only has the storage capacity for 114 liters. Just like the SOURCE panel it can be hooked into a water system to provide potable water to a specified fixture or tank.

Each device needs to have a 3-foot clearance around the perimeter and at least 15 feet of clearance above to function as efficiently as designed. As stated by the manufacturer this device works best between 15 degrees above and below the equator, as shown in Figure 3.

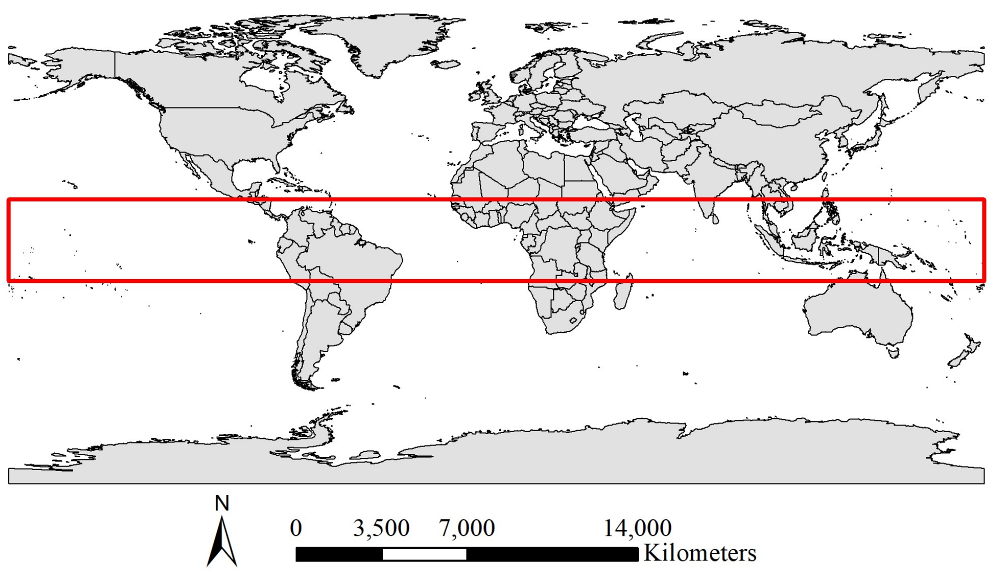


Figure 3 - World Map detailing areas 15 degrees above and below the Equator

Figure 4 - Tsunami-500 Device Picture [14]

2.2.3 Residential

The following information for the residential device was gather from an article written by Bagheri et al [1]. They investigated the performance indices of three residential devices in his paper, all the information in this section is from there.

Bagheri created an enclosure that can regulate both the temperature and relative humidity on. They took three unnamed residential sized devices, all with an optimum maximum output of 30 liters of water per day and tested them at the condition shown in Table 1. For this research the results from the first residential device were utilized.

Table 1 - Residential Device Test Enclosure Conditions [4]

Condition	T(°C)	Relative Humidity(%)
Warm and Humid	30	62
Mild and Humid	20	75
Cold and Humid	6	80
Warm and Dry	32	20
Mild and Dry	21	45
Cold and Dry	6	57
Mild	25	50

The residential device works using the same method as the Tsunami device, the refrigeration method. A picture of the device hooked up to the unit that regulates the temperature and relative humidity can be seen in Figure 5.

Figure 5 - Residential Device Testing Set Up [4]

2.3 Hydrologic Indicators

As explained in the introduction, Hashimoto et al. [5] defines reliability, resiliency, and vulnerability indicators for water resources. These metrics will be used in this research to analyze the performance of three different AWGs. The reliability, vulnerability, and resilience metrics and their application are further discussed in the methodology

Hashimoto et al [5] states that all observations at any time period, t, can be separated into two categories, either a failure or a success. This concept is used to calculate all three metrics.

- Reliability is shown as the probability of a success during any given time period. Simply, for any given set of observations, reliability is the number of successes divided by the total number of observations.
- Resiliency describes how quickly a system will rebound after a failure. It is the probability of success given a failure in the previous time period.
- Vulnerability captures the magnitude of the failure. There are much different consequences in a system if it fails only by a marginal amount versus having a catastrophic failure.

While the efficiency of a device shows an average amount of water per day it does not capture all the needed information. Such as an atmospheric water generator producing only the exact amount of needed water per day meaning a single day of failure could be detrimental. Or the fact that while the average efficiency of one device might be 40% and another 50%, the one with

lower efficiency might be more consistent or reliable throughout the year while the other one is extremely variable depending on the season. A large number of days considered failing falling consecutively could lead to the device being unable to meet the water demand at that time. Depending on the device there is a rather large difference between failing by a marginal amount and reaching 0% efficiency in a day. The three hydrological indicators, reliability, resiliency, and vulnerability will help assess this AWG technology to prevent gaps in the final analysis of its performance in the United States.

2.4 Application of the Technology

The world health organization states that at least 13.2 gallons (~ 50 Liters) of water per capita per day (gpcd) is a basic human right [15]. The residential sized unit only produces, at maximum, 30 liters of water, and the SOURCE device only produces 6 liters of water. However, these maxima are under ideal conditions that are not frequently met in real-world applications. Therefore, for these smaller types of devices, the only realistic use is either offsetting total water supply or using it only to supply drinking water. SOURCE is unique in that the units can be arrange in an array formation, with multiple units linked together, making it much more versatile in use than the residential device which is a standalone system [13].

Table 2 shows what the Air Force Handbook for base bed downs states is the required amount of potable water needed per person, this amount of water is also supplied by the bear asset ROWPU (reverse osmosis water purification unit) [16]. For this type of technology to be used at FOBs it

is expected to be just as reliable as the ROWPUs. However, to use a ROWPU, there must be a body of water to draw from, this is not the case with an AWG, making it a much more versatile device for water generation.

Table 2 - Bare Base Water Usage [16]

Functions	Water Usage (gpcd)	Water Usage (lpcd)
Drinking	4	15
Personal Hygiene	3	11.3
Shower	15	56.7
Food Preparation	5	19
Hospital	2	7.6
Heat Treatment	1	3.8
Total	30	113.6

The typical FOB is around 500 people [16], it would be very impractical to have a single device for each person. The ROWPU currently used can produce over 5000 liters of water per hour. In order to replace this with an AWG they either need to meet a water demand the ROWPU does, or function where the ROWPU cannot, like when there is not a water source to draw from. Even with the highest producing device analyzed to meet the same water capacity, 157 devices would be required. To meet the total water demand for 500 people 56,800 liters of water would have to be produced everyday which would be over 73 AWGs. This is also if they are performing at 100% efficiency. Finally, to produce only drinking water for a 500-person FOB, 7,500 liters of water would be needed every day which would be 10 devices. All these calculations were done using the Tsunami device since it produces the largest quantity of water, 773 liters of water per day. The Tsunami company has three larger capacity device than the Tsunami-500 which is the one used [14].

III. Methodology

3.1 Chapter Overview

This section will go over the process of how I gathered the data for the three Atmospheric Water Generators I analyzed in this paper as well as the 35 years' worth of weather data. It will discuss the process I used to create the spatial analysis of the efficiency percentage. Finally, it will go over how I defined and calculated the metrics reliability, resiliency and vulnerability and the locations chosen as case studies.

3.2 Data Gathering

To evaluate the Atmospheric Water Generators, a large amount of data had to be gathered, including both historical weather data and performance measures of the different AWGs. The performance data for each of the three AWG devices was utilized to create a linear regression model and used in conjunction with the historical weather data to evaluate the systems. This data can be found in Appendix C.

3.2.1 AWG Performance Data

The performance data for the three different devices used in this research were found/given in either a table or graph format. Each device had two independent variables that dictated the daily water production values. For the residential device and the Tsunami device, these variables included the temperature and relative humidity, while the SOURCE device required relative

humidity and solar energy. These observed values and performances were used to create a linear regression model, outlined in Section 3.3 and 3.4, to predict daily water outputs.

3.2.2 Weather Data

The weather data obtained from AccuWeather spanned 1935 stations across the United States for 35 years, with daily average weather [17]. The variables included in the analysis are the weather station code, latitude, longitude, date the weather was observed, solar irradiance, minutes of sunshine, relative humidity, and temperature. An R-script was created to synthesize all the weather data and transform it into a usable format for regression analysis. This was done using a function which imports all excel files into a specified folder location. Due to the large quantity of data, this step could not be completed at one time.

To handle the large amount of data the files were split into ten groups ranging from 150 to 250 files per group for a total of 1935 files, one for each weather station. The groups were determined based on the location codes to keep data from the same points together. Importing each group into R Studio took anywhere from two to three hours depending on the size of the group. Each group of files was originally imported in a list format and was converted into a singular data frame using a bind command.

Each of the ten data frames were subset so that they contained only the data required for the analysis. This helped speed up processing time, which, when analyzing this quantity of data is

very important. The date format in the data frames was all located in one column, to ease calculations of separate seasons the date was split up into three separate columns using the as.date function in R.

Finally, the ten data frames were combined and split by year so that a singular data frame contained one years' worth of data for all 1935 location codes. A function named *bind.years* was created to do this by subsetting each of the ten original data frames by a single year then binding those years together. This code was run once for each year's worth of data.

One issue that arose during this process was that once the years were separated it was found that they did not all contain the 1935 location codes. By the process of elimination an error was found in the *bind.years* function where it was subsetting one of the data frames twice and missing another one. Once this error was rectified the function was run through again and all the correct data was accounted for.

3.3 Model Building

Using the data found in Appendix C, a linear model was created for each device to predict the output of water per day. These linear models can be seen in Equations 1-3. B_0 is the intercept and B_1 and B_2 are the constants for temperature and relative humidity or solar energy.

$$SOURCE\ Daily\ Water\ Havesting\ Rate = -B_{0a} + B_{1a} * RH + B_{2a} * S \quad (1)$$

$$Tsunami\ Daily\ Water\ Harvesting\ Rate = -B_{0b} + B_{1b} * T_F + B_{2b} * RH \quad (2)$$

$$Residential\ Hourly\ Water\ Harvesting\ Rate = -B_{0c} + B_{1c} * T_c + B_{2c} * RH \quad (3)$$

In these models T_c is the temperature in Celsius, T_F is the temperature in Fahrenheit, RH is the percent relative humidity, S is the solar energy (kWhr/m^2), and all harvesting rates are reported in liters.

A separate model had to be built for each device due to the difference in the variables used and quantities of maximum water output. This section will explain the general process and the variations required for each device.

The weather data utilized had temperature recorded in Fahrenheit but as seen in Equation 3 the residential sized device utilizes Celsius so a new column in the data frame was added with the conversion to Celsius shown in Equation 5.

$$Celsius = (Fahrenheit - 32) * \frac{5}{9} \quad (5)$$

An efficiency percentage was created for each modeled output to normalize the results. This was done so that the performance of each device could better be compared since all have a vastly different maximum water output. To get the efficiency percentage the Water Harvesting rate was

divided by ideal water output of that device and multiplied by 100. Since the residential device performance was reported in the water output per hour it requires an additional step of multiplying it by 24 to get the daily water output. Equations 6-8 show this process.

$$SOURCE\ Efficiency\ \% = \frac{Daily\ Water\ Harvesting\ Rate\ (L)}{6(L)} * 100 \quad (6)$$

$$Tsunami\ Efficiency\ \% = \frac{Daily\ Water\ Harvesting\ Rate\ (L)}{773(L)} * 100 \quad (7)$$

$$Residential\ Efficiency\ \% = \frac{Hourly\ Water\ Harvesting\ Rate\ (L/h) * 24\ (h)}{30(L)} * 100 \quad (8)$$

The final step in processing the data was to split it up into the four different quarters. Quarter 1 are the months January-March, Quarter 2 are the months April-June, Quarter 3 are the months July-September and Quarter 4 are the months October-December. By splitting the data up by these months each season could be analyzed separately.

3.4 Model Assumptions and Validation

Each linear regression model for the different devices must be checked for their validity. This was done using the methods outlined in this section.

To check the first assumption for the linear model normality, the Shapiro-wilks test was used. The null hypothesis and alternative hypothesis for this test are as follows.

$$H_0 \rightarrow The\ residuals\ are\ normal$$

$$H_a \rightarrow The\ residuals\ are\ not\ normal$$

The Durbin-Watson test is used to test for independence, the null hypothesis and alternative hypothesis for this test are as follows.

$$H_0 \rightarrow True\ autocorrelation\ is\ zero (independent)$$

$$H_a \rightarrow True\ autocorrelation\ is\ not\ zero\ (not\ independent)$$

The last test is to plot the residuals and determine if the plot is homoscedastic or heteroscedastic. This tests for constant variance, the null hypothesis and alternative hypothesis are as follows.

$$H_0 \rightarrow Constant\ variance (Homoscedastic)$$

$$H_a \rightarrow Nonconstant\ variance\ (Heteroscedastic)$$

Another more reliable test for constant variance is the Breusch Pagan test. This test utilizes the explained sum of squares and the unexplained sum of squares to determine the p-value. The outputted value from the equation is then compared against the chi-squared value with the correct number of degrees of freedom. The hypothesizes are the same as the plotting test and the equation is as follows.

$$BP = \frac{\frac{SS_{explained}}{2}}{(\frac{SS_{unexplained}}{n})^2} \qquad (9)$$

In Equation 9 n is the number of factors in the linear model, in this case two, and SS is sum of squares both explained and unexplained. This test can be run in r.

The model will be validated using cross validation. K-folds cross validation method splits the data into k number of parts. It then creates k number of models from the given data and tests them against each other.

Lastly, the predicted values, from the linear models that were created, was plotted against the observed values.

3.5 Spatial Analysis

All spatial analysis was created using only the data from 2019. To do this for each separate device the first step is to create a layer in GIS with each data point, this is done by utilizing the xy event layer tool. A county shapefile was used to get the average efficiency in each county, this was determined to be the best visual for the results [18]. The county average was best because the results from the data created some zero values where there should not be when not utilizing the average values for a specific county. These zeros create hot spots on the map when

the IDW or inverse distance weighing tool is used to create the raster. This is because while utilizing the tool the value assigned to each location cannot be greater than the highest or less than the lowest input [19]. Since there are true zeros in the date frame it would take some time to weed out the ones that should not be there. By averaging the values within the county, it eliminates this error.

Averaging the efficiency over the county was done by assigning efficiency data to the county shapefile by using the average value of efficiency as the rule for spatially joining. Since there was not a single data point in every county, to prevent any gaps in the analysis the spatial join rule of 'within a distance' was used. After some trial and error, it was determined that a 50-mile radius around each county resulted in the best analysis with the smallest number of gaps.

Finally, the feature to raster tool was used over the spatial join feature to create a raster of average efficiency for an atmospheric water generator in the United States. This process was completed for all four quarters for each different device. To ensure the scaling of each map was the same, the minimum and maximum values of zero and one hundred were hard coded into some of the United States territories that are not being evaluated. By doing this and setting the scaling to use minimum-maximum it forces the color of each map to be the same scale so that a 50% efficiency on one map is the same exact color as a 50% efficiency on another map. This is important for comparison purposes.

3.6 Reliability/Resiliency/Vulnerability

Reliability is defined by Hashimoto as how often the system fails; resiliency is how quickly the system recovers once a failure has occurred and vulnerability is how significant the likely consequences of failure may be. These definitions were applied in the context of an AWG by first defining what a failure was. Using the efficiency percentage means the same failure threshold can be applied to all three devices. A 30% efficiency was first applied to the data as the failure threshold to see the general output. Using the residential device, the data showed a good spread for each metric so 30% was chosen as the final failure threshold and applied to all devices.

For an AWG reliability is defined as the probability the device is in a successful state at any given time step. Figure 6 shows a visual representation of example data. Each point represents one days' worth of data. Utilizing the failure threshold of 30% every point that is above that is highlighted. Since they are above the threshold each of the highlighted points would make up the reliability percentage.

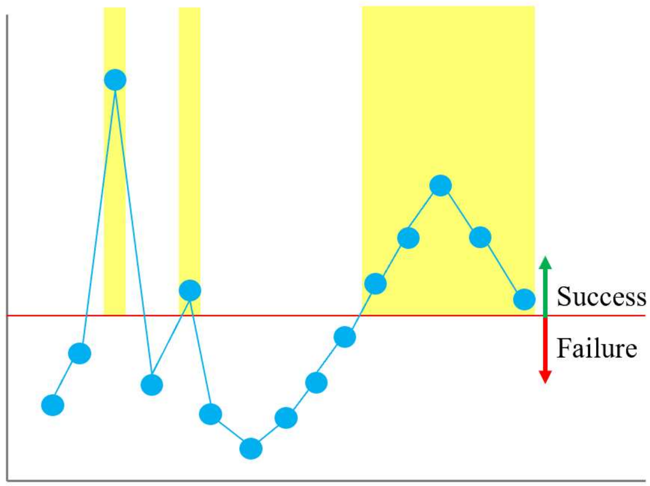


Figure 6 - Reliability Visual

To calculate reliability an ifelse statement was created where anytime the systems efficiency was below the set failure threshold, the dummy variable would be equal to a value of 0 and if it were above the failure threshold the value was set to be 1. For each quarter, the percent reliability was calculated by summing the dummy variables and dividing it by the length of that vector and multiplying it by 100, this can be seen in Equation 10. This means that a 0% reliability means that the AWG never left a failure state during the observed period and a 100% reliability means it never entered a failing state.

$$Reliability\ \% = \frac{Number\ of\ Times\ Successful\ in\ a\ Year}{Number\ of\ Days\ in\ a\ Year} * 100 \qquad (10)$$

For the AWG resiliency was defined as the probability that if the current day is below the set failure threshold the next day will be above the threshold. Looking at Figure 7, since each point represents a day resiliency is the probability percentage that when day 1 is in a failure state that day two will be in a success state.

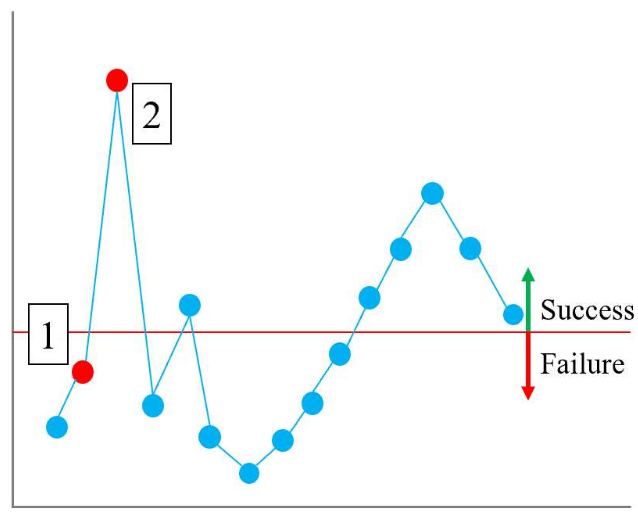


Figure 7 – Resiliency Visual

To evaluate this metric another column was created by taking the reliability variable and shifting the column up one. That way in a single row both the current state of the device and the state of the device for the next day can be referenced. Another dummy variable was used to define if the device was resilient for any given two-day period. If both the current day and next day were zeros, meaning the device stayed in a failure state, then the resilience was also equal to zero for that instance because the device did not recover from a failing state. However, if the current day

is zero and the next day is 1, meaning it's in a successful state then the resilience dummy variable is equal to one for that instance. This was executed with a series of ifelse statements in R Studio.

Just like with reliability the final metric for resiliency was calculated as a percentage. Taking the sum of the total number of times the system recovered from a failing state and dividing it by the total number of times it was in a failing state and multiplying by 100, this can be seen in Equation 11.

$$Resiliency\ \% = \frac{Success\ in\ time\ t|\ Failure\ in\ t-1}{Number\ of\ Failure\ in\ year} * 100 \tag{11}$$

For the AWG vulnerability was defined as, the maximum average failure. Looking at Figure 8, it shows the failure threshold, and the vulnerability is the distance away from that threshold. Instead of reporting this in efficiency percentage it was reported in the maximum average of expected liters deficient from the failure threshold.

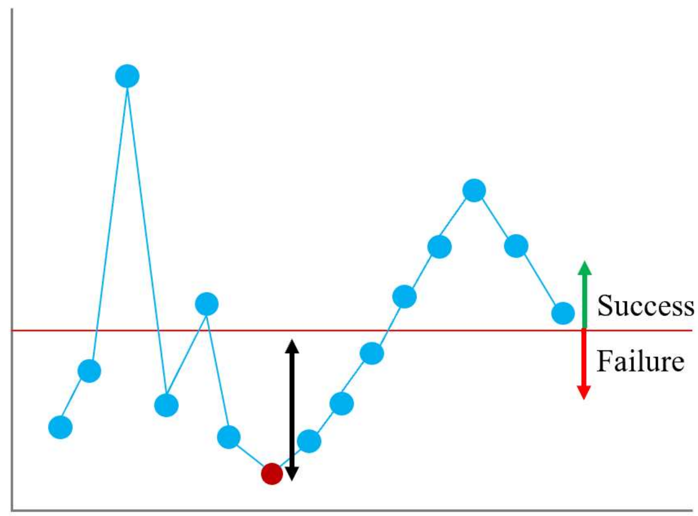


Figure 8 - Vulnerability Visual

This was done by first using a grouping function in R to create a new column of group numbers. Anytime the reliability variable switch from 0 to 1 or 1 to 0, so from a successful state to a failure state or vice versa a new group number was created. This allowed for grouping each of the failure periods together. The data frames were then aggregated over the efficiency percentage by taking the average efficiency for each grouping.

Depending on the season and device this created anywhere from 1 to 20 different vulnerability groupings. Since only the failing states were being looked at any instance the system was not failing was grouped together. For each instance of failure, the number of days of each failure was also calculated, or the number of days the system was deficient. The efficiency of the device was

then converted into the number of liters of water it would produce in a 24-hour period deficient from the failure threshold. Equations 12-14 were used to produce this deficiency from failure.

$$SOURCE\ Liters\ Deficient = \left(Failure * \frac{6}{100}\right) - \left(Efficiency * \frac{6}{100}\right) \quad (12)$$

$$Tsunami\ Liters\ Deficient = \left(Failure * \frac{773}{100}\right) - \left(Efficiency * \frac{773}{100}\right) \quad (13)$$

$$Residential\ Liters\ Deficient = \left(Failure * \frac{30}{100}\right) - \left(Efficiency * \frac{30}{100}\right) \quad (14)$$

The final metric reported for vulnerability was determined by using the max function over the liters deficient.

All three metrics were then wrapped up into a function which requires the data frame, the weather station code, and the failure threshold to run.

Since this function looks at each location code separately, a for loop was created to run a single year of data through for each location. This was done by running the for loop for all unique values in the weather station code column of the data frame. The results were then combined into an output data frame by using the rbind command to add each new row of data for all 1935 unique location codes. The final results data frame holds the following variables for each location, weather station code, latitude, longitude, year, average efficiency, reliability, resiliency, and vulnerability for each quarter and annual.

To be able to compare the 35 different years efficiency all 35 separate results data frames for a single device were combined using the rbind command.

3.7 Case Studies

To better analyze the three different metrics described in the previous section four bases were selected to pull out and visualize their data for comparisons. These bases can be seen in Figure 9. Originally six bases were chosen, but Hill AFB (UT) and Laughlin AFB (TX) showed minimal variance from their neighbors. Hill AFB never even passed the failure threshold of 30% efficiency for either the residential or tsunami device, so these two points were eliminated to have more concise results.

The four Air Force bases were chosen due to their locations and climates as well as the results from the initial efficiency maps from the residential device. Using the Koppen-Geiger climate classification system Cannon AFB is BWk or a desert/arid climate, Fairchild AFB is CSa or Hot-summer Mediterranean climate, and both Hurlburt Field and Joint Base Andrews are CFa or Humid subtropical climate [20]. Even though Joint Base Andrews and Hurlburt Field are classified the same, the preliminary check of efficiency showed that the performance of the AWG varied greatly each season at Andrews but was much more consistent throughout the year at Hurlburt which is why both were selected.

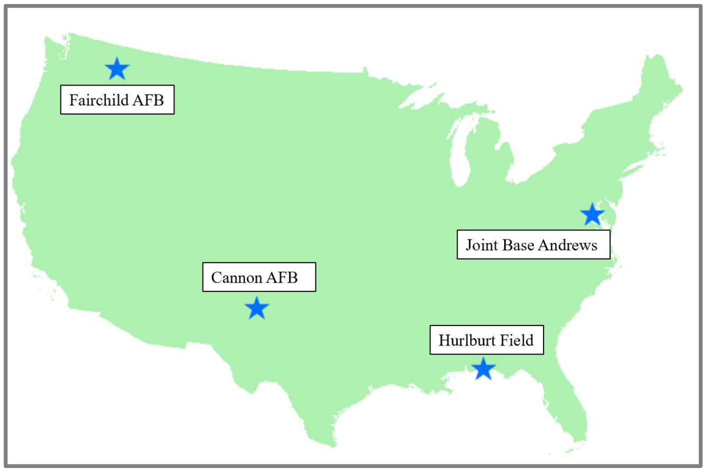


Figure 9 - Map of Case Studies

Using the same locations shown in Figure 9 and the previously determined values for efficiency, reliability and resiliency were used to graph the values across the years 1985 to 2019. This was done to see if there was any discernable trend as the years progressed.

IV. Results

4.1 Model Building Results

Equations 15-17 are the resulting linear regression models for each different device from SOURCE, Tsunami and Residential.

$$SOURCE\ Daily\ Water\ Havesting\ Rate = -2.739 + 0.0474 * RH + 0.841 * S \quad (15)$$

$$Tsunami\ Daily\ Water\ Harvesting\ Rate = -1716.07 + 17.4 * T_F + 13.14 * RH \quad (16)$$

$$Residential\ Hourly\ Water\ Harvesting\ Rate = -0.8358 + 0.02659 * T_c + 0.01012 * RH \quad (17)$$

The summary of each model showing the coefficients and R2 value can be found in Appendix B. The first model shown in Equation 15 has an adjusted r squared value of 0.954, the second model in Equation 16 has an adjusted r squared value of 0.906 and the final model shown in Equation 17 has an adjusted r squared value of 0.807. This shows that for each model the variables account for, on the low end, 80% of the variability in the hourly or daily water harvesting rate.

4.2 Model Validation Results

For all the completed tests, if needed the assumed alpha value was 0.05. If the P-value, which is the reported value, is above 0.05 then the test fails to reject H_0 for that test, this is the desired result to validate the model. If the P-value is below 0.05, the assumed alpha value, then H_0 is

rejected and H_a is accepted for that test. The results from all the tests can be found in Table 3. For all three tests, Shapiro-Wilks, Durbin-Watson, and Breusch Pagan the only instance where the model does not pass is the Tsunami device for the Durbin-Watson test, or the test for autocorrelation. This means the Tsunami device model is not independent.

Table 3 - Linear Model Test Results

Test	SOURCE	Tsunami	Residential
R^2	0.95	0.90	0.81
Shapiro-Wilks (P-value)	0.1824	0.07372	0.6474
Durbin Watson (P-value)	0.1345	1.846e-13	0.4729
Breusch Pagan (P-value)	0.2879	0.295	0.1491
Residual Standard Error	0.2168	108.3	0.0841
K-folds Cross Validation (RMSE)	0.2206974	108.57	0.1476

Figure 10 shows the plot of the residuals versus the independent variables, this tests for constant variance. The results from the test look to be heteroscedastic for the three devices. However due to the minimal amount data points, especial for the residential device it is hard to tell. Because of the vague results further testing for constant variance was completed using the Breusch Pagan test, these results can be found in Table 3. All values are above the 0.05 alpha value so fail to reject H_0. This is the wanted results from the test and further validates the models.

The last test completed is the K-folds Cross validation test. The RMSE or the root mean squared error, of this test is compared to the residual standard error from the original linear model. The goal of this cross validation is to have the two values be as close as possible, for each device the values are within a small factor of each other which then validates the model.

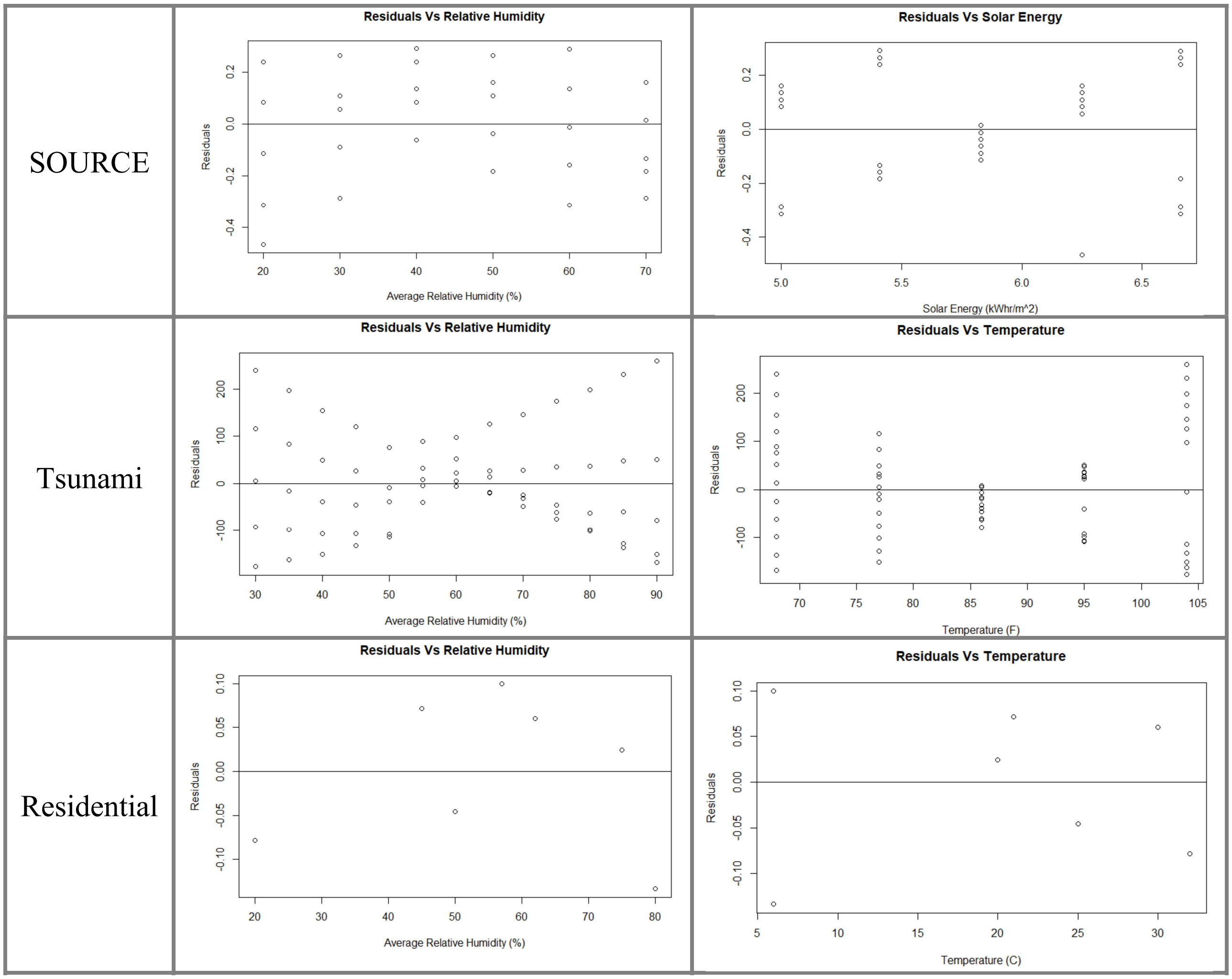


Figure 10 - Residuals Plots

The last results gotten from the individual device water output data is plotting the observed values versus the predicted values. The results from this for each device are shown in Figure 11. A 45 line was drawn on each plot, ideally there would be 50% of the results on either side of the line. This is certainly the case with all devices even though Tsunami has a small deviation at a low output volume.

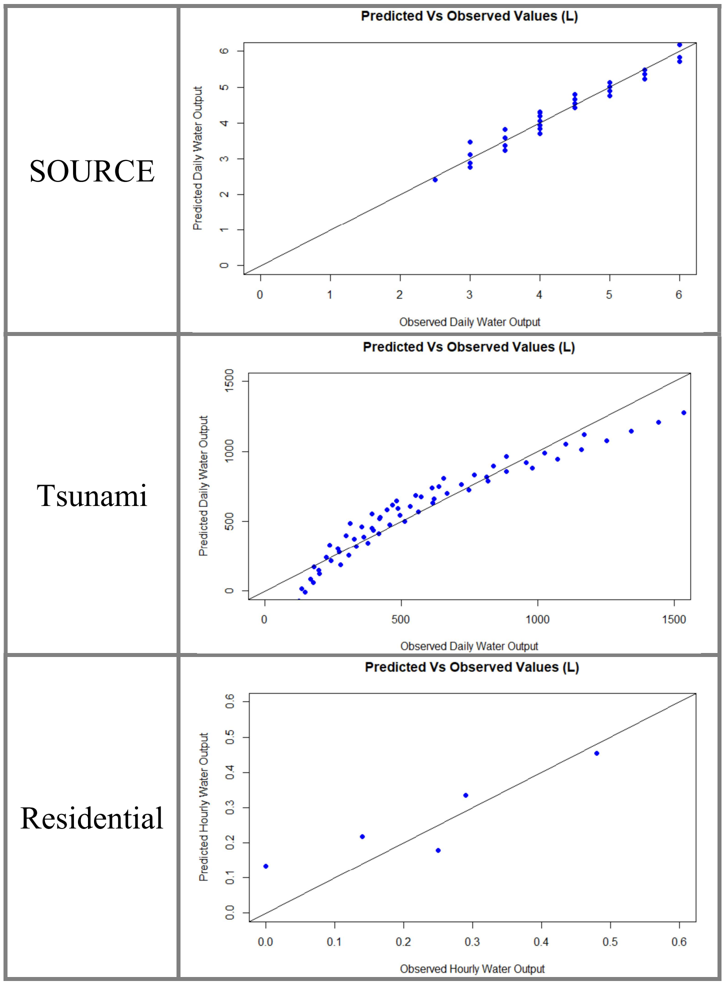


Figure 11 - Predicted Vs Observed Plots

While validating the linear model is not a necessary step to create the final efficiency raster, it helps provide valuable information on how reliable the efficiency data is.

4.3 Spatial Analysis Results

The Residential device's initial spatial analysis results are shown as raster map in Figure 12. It represents the efficiency percentage created using the inverse distance weighing (IDW) tool on the Residential devices quarter 3 efficiency data.

Figure 12 shows that there are many 'hot spots' in the data or areas where there is a lower value than is expected. Typically, this type of error could be eliminated by selecting all the problem points and removing them from the analysis. However, since there are so many data points and some points do contain 0% efficiency when they should there is no easy way to remove these points. Because of this the IDW tool output was not used for the final analysis. The IDW raster method takes all the data points into account when creating the raster while the spatial join only utilizes the average value point for each county. Which is why, given the data, the spatial join is the best method to perform the spatial analysis.

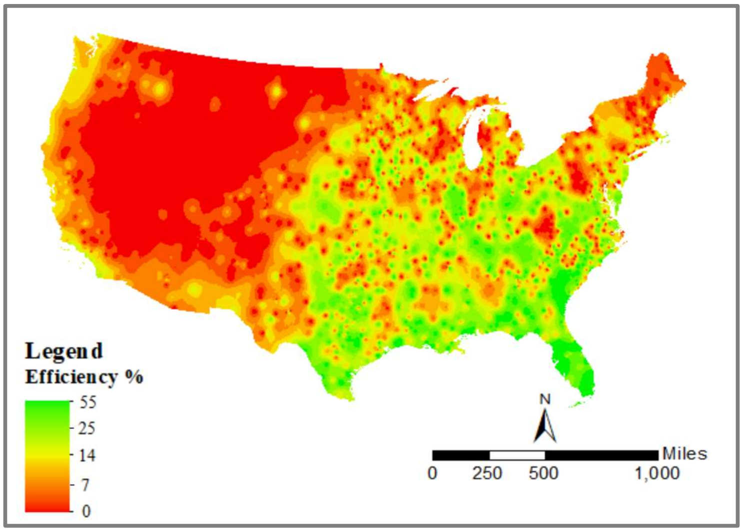


Figure 12 - Residential Device IDW Raster

Figure 13 shows the final efficiency output from the spatial join method for each quarter for each device. First looking at the results for the SOURCE device, for each quarter it has the highest overall efficiency of any device. This correlates with the fact that, since it works off the sorption method it works in lower relative humidity levels. So, in places like Utah where it is a very hot but dry climate in the summer it performs much better than the other two devices that use the refrigeration method. Since SOURCE uses solar irradiation instead of temperature to determine its water output per day, it is affected by locations that either have more or less sun depending on the season. Looking at the results for Quarter 4, it shows a decrease in efficiency at the top of the United States where the amount of sunlight per day is decreased significantly. Appendix A shows the efficiency results for Alaska. Alaska shows the lowest efficiency for SOURCE out of any other location in quarter 4 this can be attributed to the limited amount of sunlight during those months. All the calculations for the SOURCE device were calculated under the assumption

it received all the possible sunlight during any given day however since the solar panels do not track the sun this is not possible. Therefore, it is expected that the actual efficiency of the SOURCE device in any given location to be lower than what is shown in Figure 13.

Next looking at the Tsunami device in Figure 13, the gradient shown in quarters 2 and 3 is exactly what was expected for the warmer months, in the colder and very dry climates there is little to no efficiency from the atmospheric water generator. While in the warmer and more humid climates, like Florida and Georgia, the Tsunami AWG has as great as a 95% efficiency in some areas. Tsunami's raster imagines also show clear distinction in the efficiency around where the mountain ranges are and close to the coast. This is expected due to how mountains and the ocean affect the surrounding climate.

Looking at the different quarter outputs for the device it shows a large range of Tsunami's efficiency. This is very logical considering the linear models' inputs to create the water harvesting rate are only based off temperature and relative humidity. Therefore, the device potentially works best in a region between 15 degrees above and below the equator due to the warm and humid environments as well as the little to no variation in the seasons [14]. This smaller seasonal variation can be seen in Figure 14 showing Hawaii's efficiency for each device.

Lastly the Residential device shows the worst overall efficiency. This makes sense considering the data that was used, the device only reached a maximum of 60% efficiency in the best-case

scenario, which looking back at Table 1 in Section 2.2.3 is 30°C and 62% relative humidity. However, even though it has an overall lower efficiency looking at quarter 2 and 3, the higher efficiency areas follow the same trend as the Tsunami device.

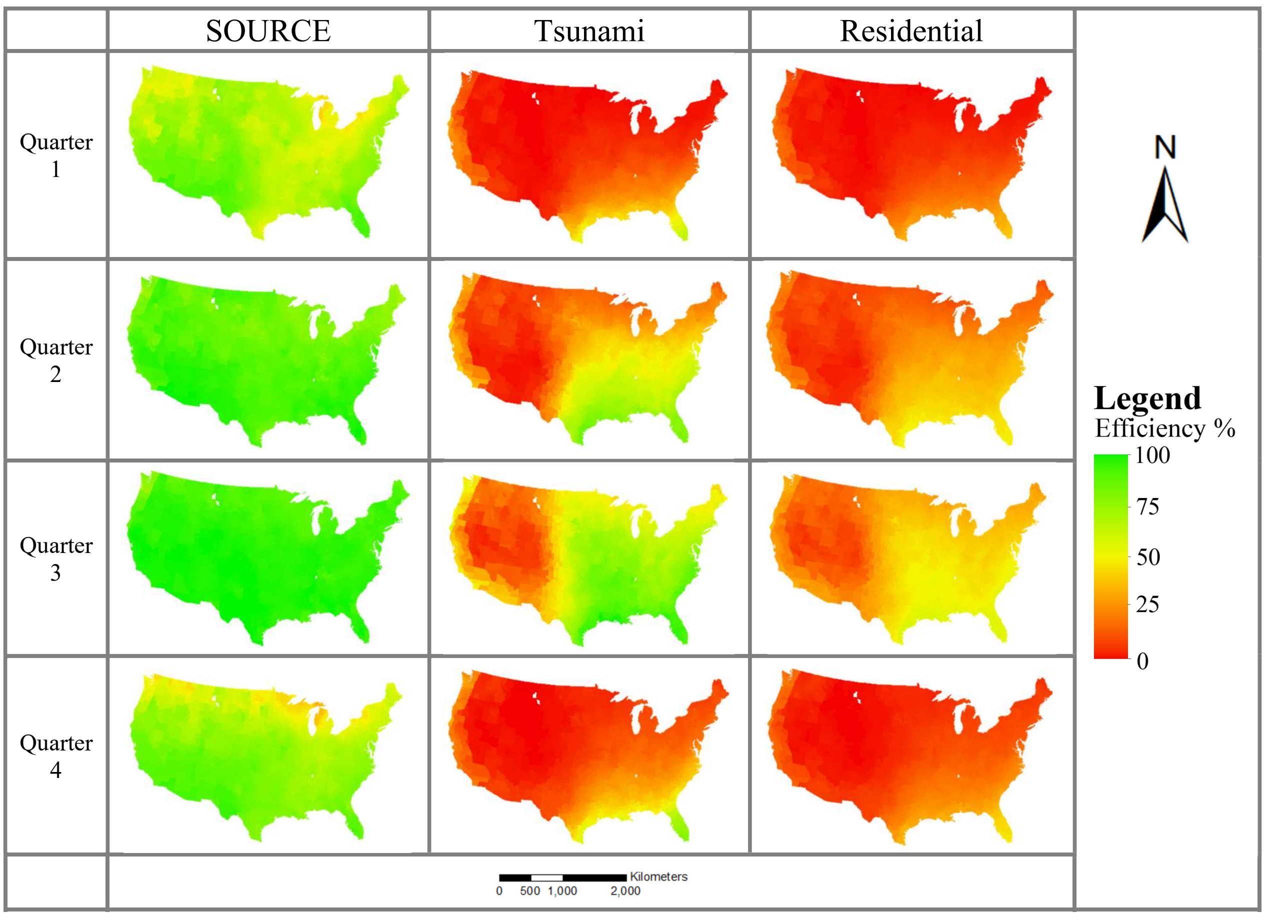


Figure 13 – Continental United States AWG Efficiency Raster Maps

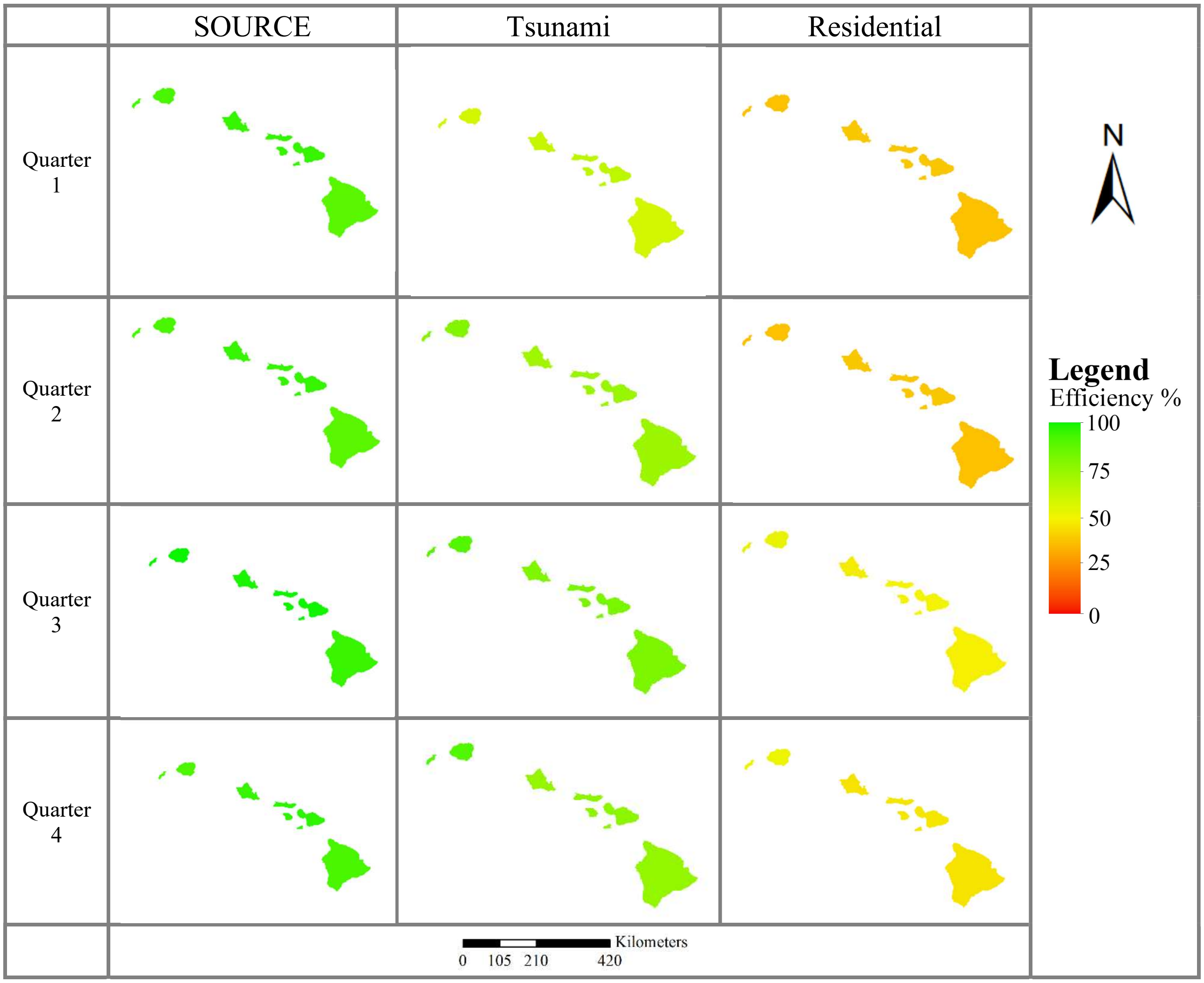


Figure 14 - Hawaii AWG Efficiency Raster Maps

4.4 Reliability/Resiliency/Vulnerability

Using the steps explained in the methods section each metric was calculated for each device. Figures 15-17 show the results at each of the four bases. As expected from looking at the efficiency map the SOURCE device has the best reliability and resiliency followed by the Tsunami device and then the Residential device. Since the failure threshold was set at 30%

efficiency the residential device only falls just short of Tsunami, however if the failure threshold was set higher it is expected a much larger gap would be seen.

Looking at Figure 15, which shows the reliability of each device at all the locations, they follow the same trend where quarter 3 has the best performance followed by quarter 2. The SOURCE device performs remarkably better than the other two in the drier colder locations of Cannon AFB and Fairchild AFB. However, they are more evenly matched at warmer more humid climates of Joint Base Andrews and Hurlburt Field.

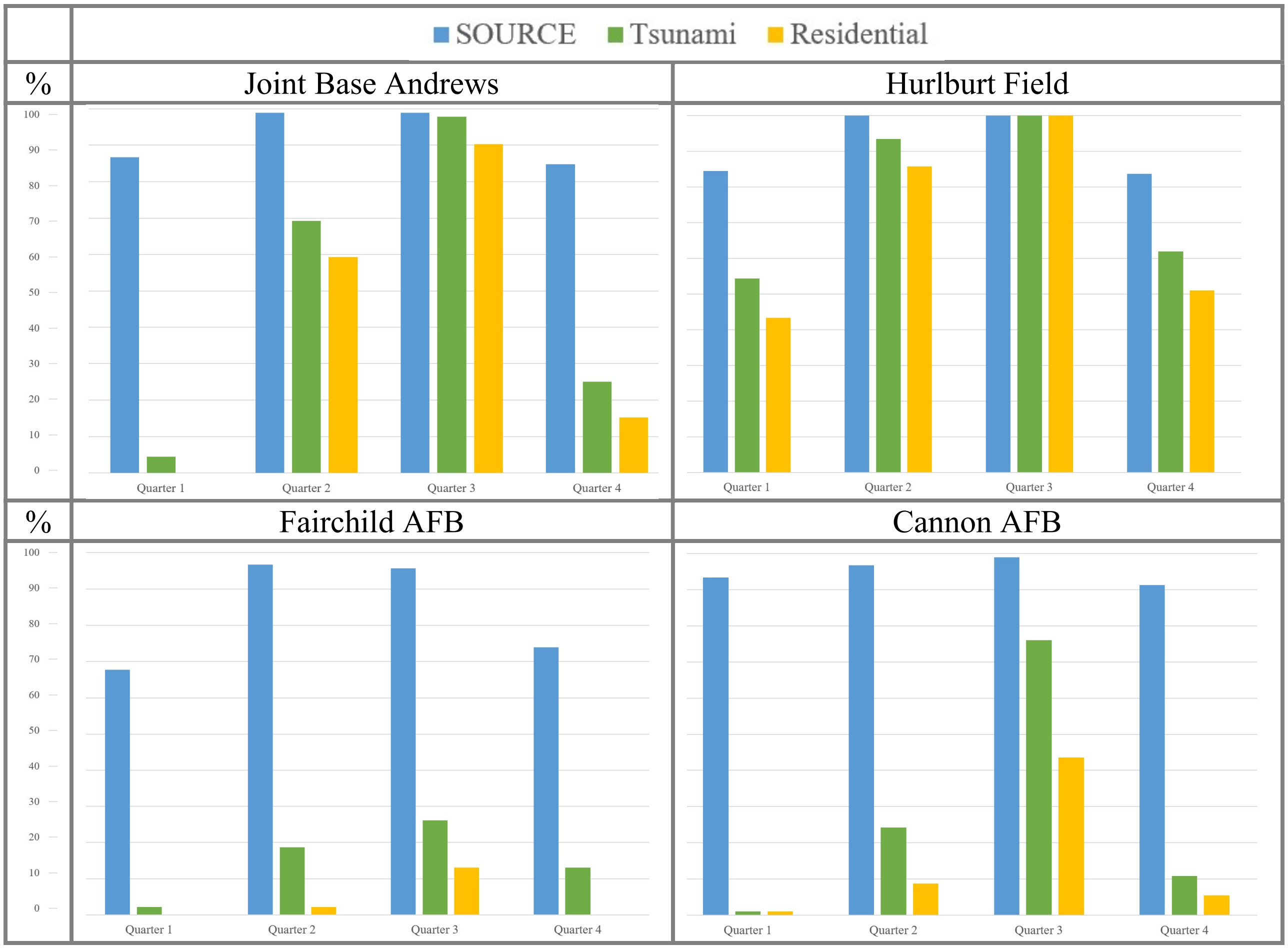


Figure 15 - Reliability Results

Looking at Figure 16, at most locations resiliency for any device does not get over 60% except for the SOURCE device at Fairchild and Cannon. For resiliency, the areas where there is no data does not mean the device is not resilient during that quarter, it means that the device did not go into a failure state so it can not go from a failure to a success. Just like with reliability SOURCE performs the best at all locations and Tsunami is second except for quarter 4 at both Joint Base Andrews and Hurlburt Field. Future data analysis comparing the two devices at other locations

would have to be preformed to understand why the Tsunami device underperforms compared to the residential device in only those two instances.

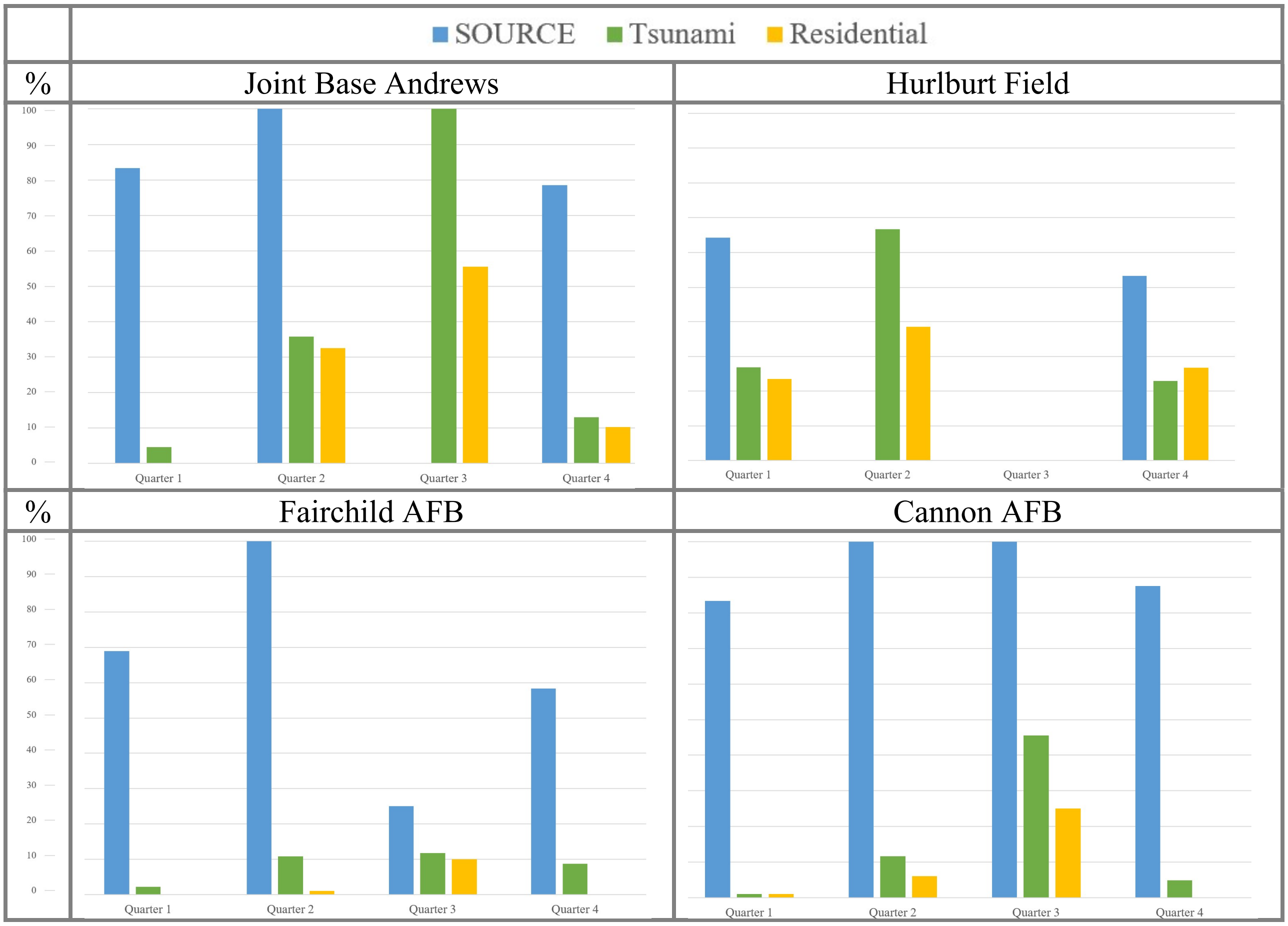


Figure 16 - Resiliency Results

Since each device maximum output is vastly different, that means their vulnerability or max average deficiency is also very different. To better compare the three devices, the two with lower capacity, the residential and SOURCE, were normalized to be able to reach the max capacity of the Tsunami device. This was done by multiplying the vulnerability by the number of devices

required to reach the capacity of the Tsunami. For SOURCE this meant multiplying it by 129 to reach just over the capacity of 773 liters of water per day. For the residential device this meant multiplying it by 26. Whole numbers were used since you cannot use 1/3 of a piece of technology.

Figure 17 shows the vulnerability for each device, with the normalized for the smaller devices. Normalized values being those that outputs match the largest capacity device, Tsunami. To note in Figure 17 at Hurlburt Field there is no data for quarter 3, this is because all devices never enter a failure state during that quarter so they cannot be deficient from the failure threshold.

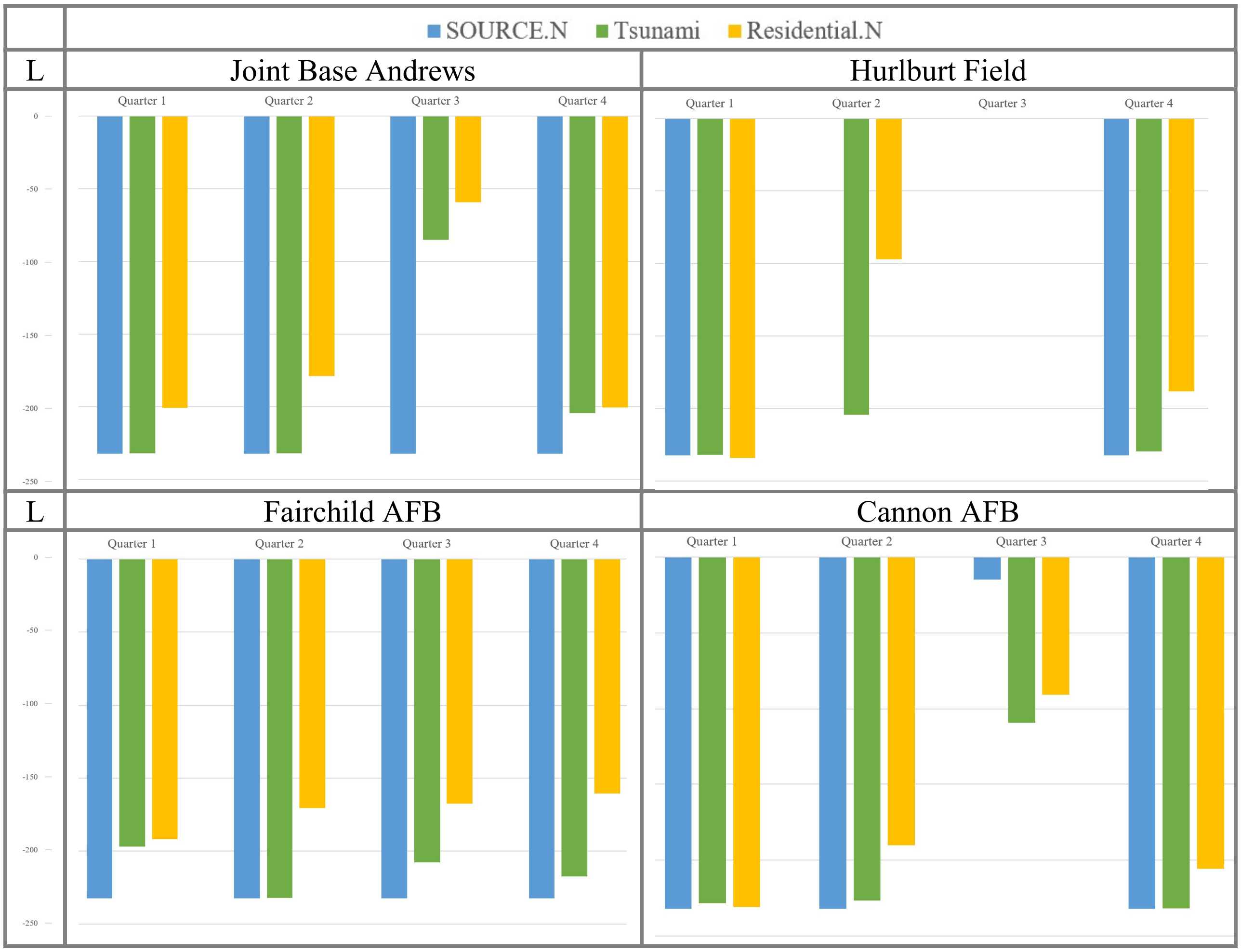


Figure 17 - Vulnerability Results

Looking at the results it shows that while the residential device performs overall the worst in the other metrics, when it does fail it fails by the smallest amount for all locations and quarters.

4.5 Case Studies/Results Across the years

The final analysis performed was plotting each devices efficiency, reliability, and resiliency over the course of the 35 years' worth of historical data, 1985-2019 [17]. This was completed to see if there is any discernible trend to the data as the years progress.

Both the Tsunami and Residential device bounce around, going up and down during the same years. This makes sense because both use the refrigeration method, so they will be affected by the varying temperatures and humidity's in the same manner. The SOURCE device on the other hand shows a considerable trend upwards for both the efficiency and reliability in the last 15 years.

Figure 18 - Metrics over the 35 Years

V. Discussion

5.1 Results

Looking at Figure 13, the efficiency mapping, it is clear the SOURCE panel outperforms the other two devices in all seasons. Due to the methods the devices use, sorption and refrigeration, from this it shows the sorption device outperforming the refrigeration devices. This makes sense given that the sorption device works well in far lower relative humidity levels than the other two types. However, this comes at a cost, sorption devices, based on current research, produce far less quantities of water than the other two methods. So, while it is more efficient, it still might not be the best device depending on its intended use.

The Tsunami device outperforms the residential sized device and looking at the reliability metrics it shows that for each season and each location the Tsunami device preforms better by relatively the same amount. The United States consists of 10 different climate zones [21]. Due to the considerable reliance all atmospheric water generators have on the weather it stands to reason that the performance of the AWG will vary greatly throughout the Unites States. Both the Tsunami and the residential device prove this, looking at Figure 13, especially the Tsunami devices results show the different climate zones through the different quarters. If the residential devices results were scaled differently, they show a similar pattern, this can be seen in Appendix A.

The resiliency of each device follows the same trend as their reliability. The SOURCE device performs the best in each location and season, and Tsunami and Residential devices follow. This shows that for atmospheric water generators that the devices that perform better are more likely to come back from a failure than those that perform poorly. With the knowledge of its reliance on the weather and climate of the region this comes as no surprise due to the intermediate weather changes. During the seasonal changes a well performing device will likely switch from failure to success quite often, while lesser device would likely enter a failure state and stay there unless there are large fluctuations in the weather.

What was surprising is that while the SOURCE device outperformed the other two in every other category, it performed the worst of the three for Vulnerability. SOURCE had the largest possible deficiency in water across the board. Meaning that when it failed it was not producing any water. This occurred for all four case study locations in every season. Meanwhile the Tsunami device, which was the only one not scaled up, and the residential device still produced water even when they were in a failure state during a some quarters at the different locations. While this might be due the fact that the SOURCE device produces a much smaller amount of water, 0.7% of what Tsunami produces and 20% of what the residential device produces, it could also be because it utilizes the sorption method and the other two do not. An additional analysis, with the same outputs for vulnerability with a secondary sorption device would have to be conducted to verify the cause.

As pointed out in the results section the only device that had an upward trend over the 35 years is the sorption device. This device, unlike the others that use temperature, utilizes solar irradiance to predict the potential water production rate. Utilizing the data from Accuweather [17] solar irradiance was graphed which shows a significant increase over the years, this can be seen in Appendix A Figure 21. This accounts for the difference between the outputs of the three devices and shows how within the last 15 years the sorption method has become significantly more effective in the United States.

5.2 Similar Research

Lord et al [22] investigated atmospheric water generators and how they could solve the lack of drinking water for around 1 billion people. They selected water production levels for different relative humidity percentages per day so that it would meet the targeted goal of five liters of drinking water per day per person and chose two different devices with potential yield that met these parameters. From their mapping the AWG, it shows they have the highest yield right around 15 degrees above and below the equator, which was stated before as the best location for use. They next calculated the amount of drinking water in areas without access to potable drinking water with a theoretical yield of an AWG at that location. They then mapped the number of hours of certain levels of relative humidity during the day globally. The hope is to use this information to aid in the development of a solar power AWG.

They found that most areas that lacked a safely managed drinking water system (SMDW) are right around 15 degrees above and below the equator. Which is also the locations they found the AWG to work best. This coincides with the results from my analysis as well showing that while the technology does work in the United States, especially the refrigeration devices are not reliable with how they currently function.

5.3 Real World Applications of AWGs

One motivation for this research was to determine the feasibility of this technology at a foreign operating base (FOB). Typically, a FOB is around 500 people. If the location of the FOB were to have a similar climate to Florida, then to ensure enough water is suppled it should be estimated the device will only perform at 60% efficiency. Florida has on average a 60% efficiency rate for the devices looked at in this research. The goal of the AWG would be to provide the minimum amount of water per person for a FOB which would be 56,800 for a water needs and 7,500 for just drinking water. To meet the water demand at the 60% efficiency level the project amount of water produced each day would have to exceed 79,520 liters for all water needs and 10,500 for only drinking water. Tsunami's largest device produces 7,200 liters of water per day however at that size it loses its mobility which might make it unsuitable for use at a FOB depending on the timeline for use.

So instead of looking at providing water for such a large amount of personnel with water at more transient locations I looked at different possible uses. The 611th Civil Engineering Squadron

(CES) is based out of JBER, Alaska but controls the infrastructure for 21 remote locations across Hawaii, Alaska, and Wake Island. Two of those locations in Hawaii, Ka'ala and Koke'e are minimally- manned radar sites staffed by the Hawaii Air National Guard. Both locations are on the top of mountains, one of which is located at 4,025 ft in elevation on top of Mt Ka'ala. Based on the information gathered from the water resource manager in the 611 CES both sites have been without proper potable water systems in the recent years. At Ka'ala there is a filtration system of both sand and chlorine, the water comes from a rain catchment system however right now the chlorine system is being bypassed and the sand filtration is subpar, leaving the water with elevated TDS levels significantly above the recommended limit. Recently, 250-gallon cisterns have been utilized on this site for drinking water purposes, but previously water was brought on site via 5-gallon drums whenever the site was going to be in use. At Koke'e there is no functional filtration system on site, when the site is in use water is brought up in jugs.

Both sites would require around 7,570 liters of water per day based on the number of personnel. This number however is based on peak demands when there are 20 people on site during training weekends. Typically, these sites are only occupied by around 5 people which would bring the water requirement down to 2,400 liters per day. Based on the results shown in Figure 14 AWGs perform much better throughout the year in Hawaii than in the continental United States. This coincides with Lord et al results which showed AWGs working best 15 degrees above and below the equator [22]. Based on this information and the results of all three devices, the potable water issue at Ka'ala and Koke'e could be solved with the use of an AWG. They have lower water

requirements, and their water storage tanks are still usable, it is just the filtration and disinfection systems which are not performing as they should.

Under the assumption training weekends happen only once a month if they use one of Tsunami's larger systems that produces 3,600 liters of water per day in conjunction with a 20,000-liter gallon water tank they would meet both their daily and peak demand needs. However, the efficiency of the Tsunami-500 gets as low as 75%, in which case, if a peak weekend lasts four days they would be short about 10,000 liters of water. This remaining amount of water could be covered by either buying a secondary device to use just during peak weekends or finding another supplementary source of water.

5.4 Recommendations for Future Research

It is recommended that future research be done to investigate the energy consumption of each atmospheric water generator device. This could be done for various levels of efficiency of the devices. The performance of the AWG can also be projected globally using the linear regressions created, given access to the needed weather data. The energy consumption research could aid in determining a price per liter of water cost as well as determining the systems compatibility with solar power. Projecting the performance of the AWG globally will show how the device performs in all climates found globally instead of just those found in the United States. In order to be able to use this technology more reliably advances need to be made specifically in the sorption methods water collection ability and in the refrigeration methods efficiency.

VI. Conclusion

Both the efficiency raster maps Figures 13 and 14, and the three different metric outputs, Figures 15-17, show a large variance in how well an atmospheric water generator performs in the United States given the different seasons. However, the SOURCE device is as much as two times more efficient than the two devices which operate on the refrigeration method. The SOURCE device utilizes the sorption method leading to the conclusion that this method is the most efficient in climates found in the United States. As it stands right now devices that operate with this method produce on average far less quantities of water than the other two methods.

The seasonal variation of the refrigeration method, ranging from 0% to 98% reliability at Joint Base Andrews alone, makes a refrigeration-based AWG an unreliable source of water generation for the continental United States. Quarter 3 sees the best performance for all devices at all locations while quarters 1 and 4 see that worst performance for all devices at all locations.

The sorption method can be seen with an average efficiency above 70% year-round at all locations, but as stated before the quantity of water produced per device is on average the lowest and would be inefficient for a larger group of personnel. Because of this, as it stands right now the use of an AWG as a sole source of water is not recommended.

In locations like Hawaii a refrigeration device sees on average above 40% efficiency for a standard device and above 60% efficiency for an advanced device year-round. So, while an

AWG is not worth the investment in the continental United States right now in locations with climates similar to Hawaii, for small populations of personnel in rural areas it can be used as a good solution to any potable water needs. Like the examples given before of Ka'ala and Koke'e Air Stations.

Most devices that produce potable water like the ROWPU require a body of water nearby or ground water to draw from. In some locations however there might not be anything available to draw from. So, while atmospheric water generation may not be as reliable for potable water its versatility makes it an important technology. Due to its unique function and mobility, an AWG can be a very usefully technology as a supplemental water supply or to primarily supply only drinking water. For a deployed location instead of shipping out cases and cases of water bottles a few of these devices could be used instead. This would not only save space but is also a much more environmentally friendly option. An AWG can also be deployed in cases of a natural disaster to provide much needed water without the requirement of built infrastructure. Until the sorption method devices are able to catch up to the refrigeration-based devices in the capabilities of amount of water produced per unit they are not worth the investment at this time.

Appendix A

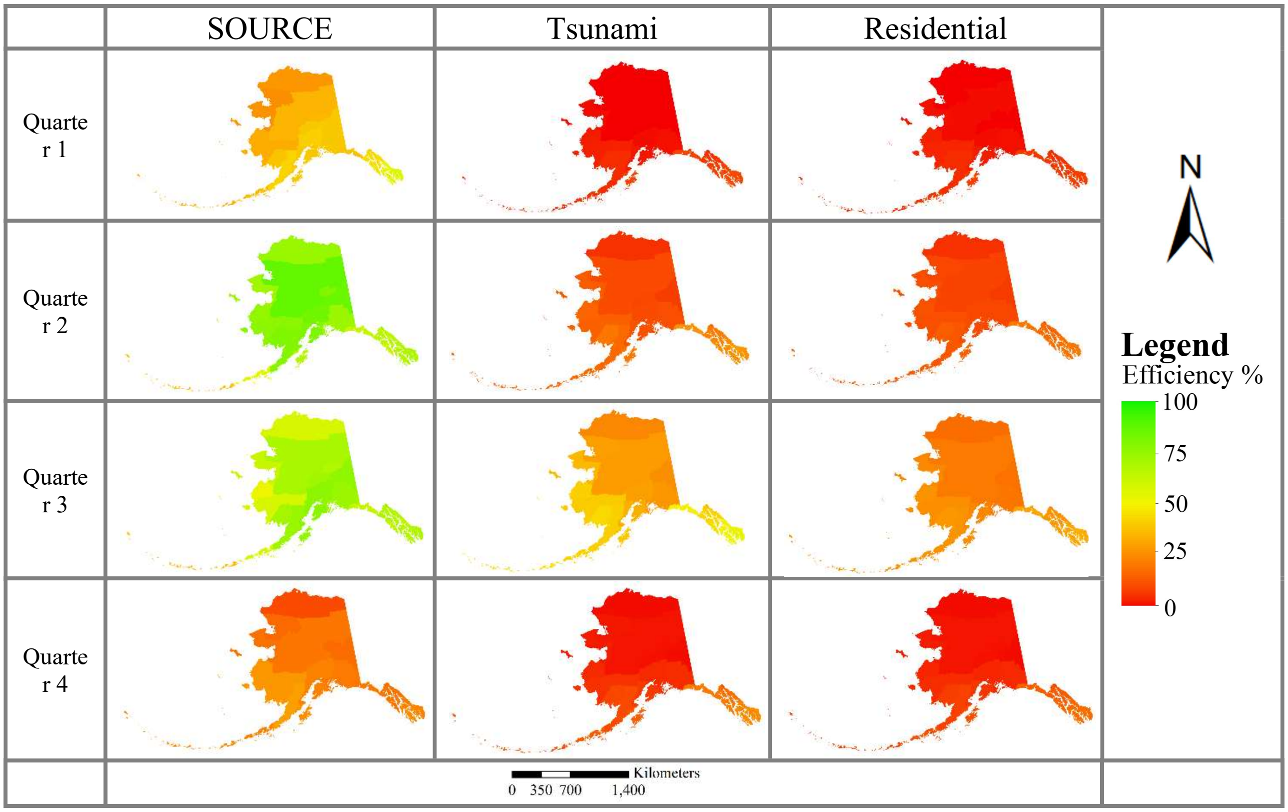


Figure 19 - Alaska AWG Efficiency Raster Maps

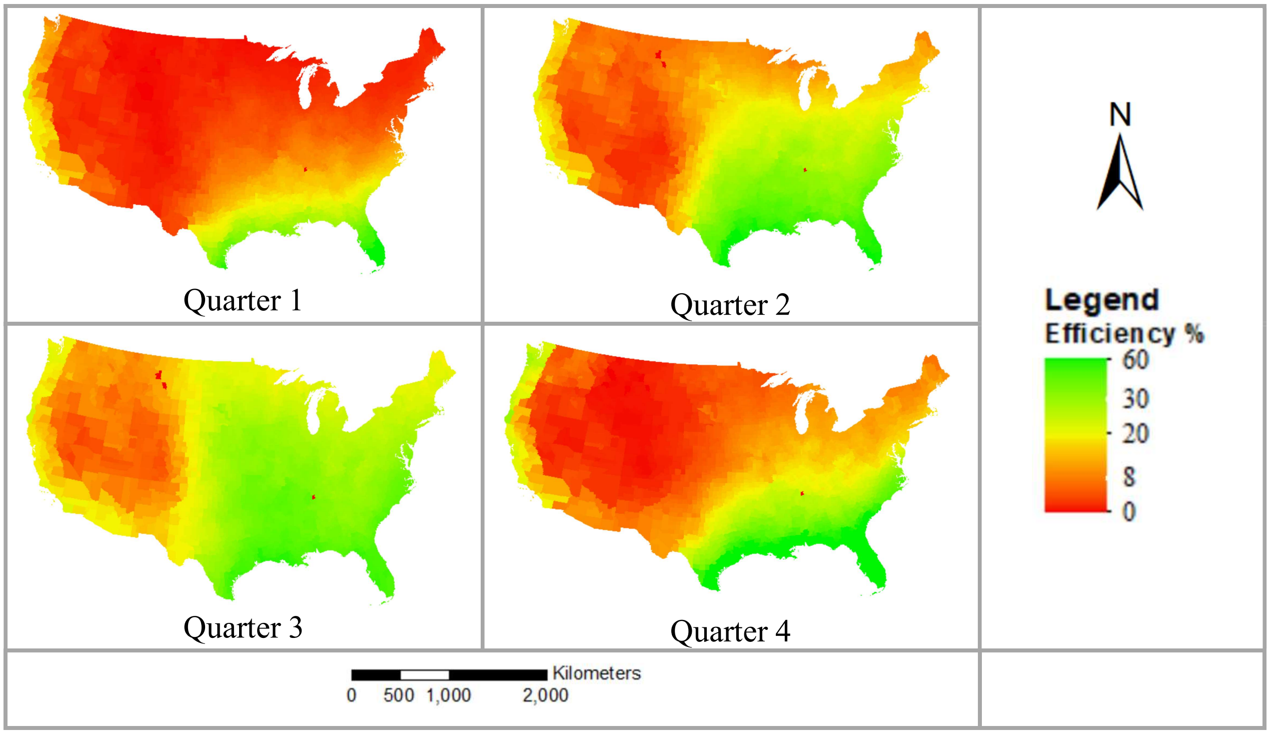


Figure 20 - Residential Sized device un-adjusted efficiency raster maps

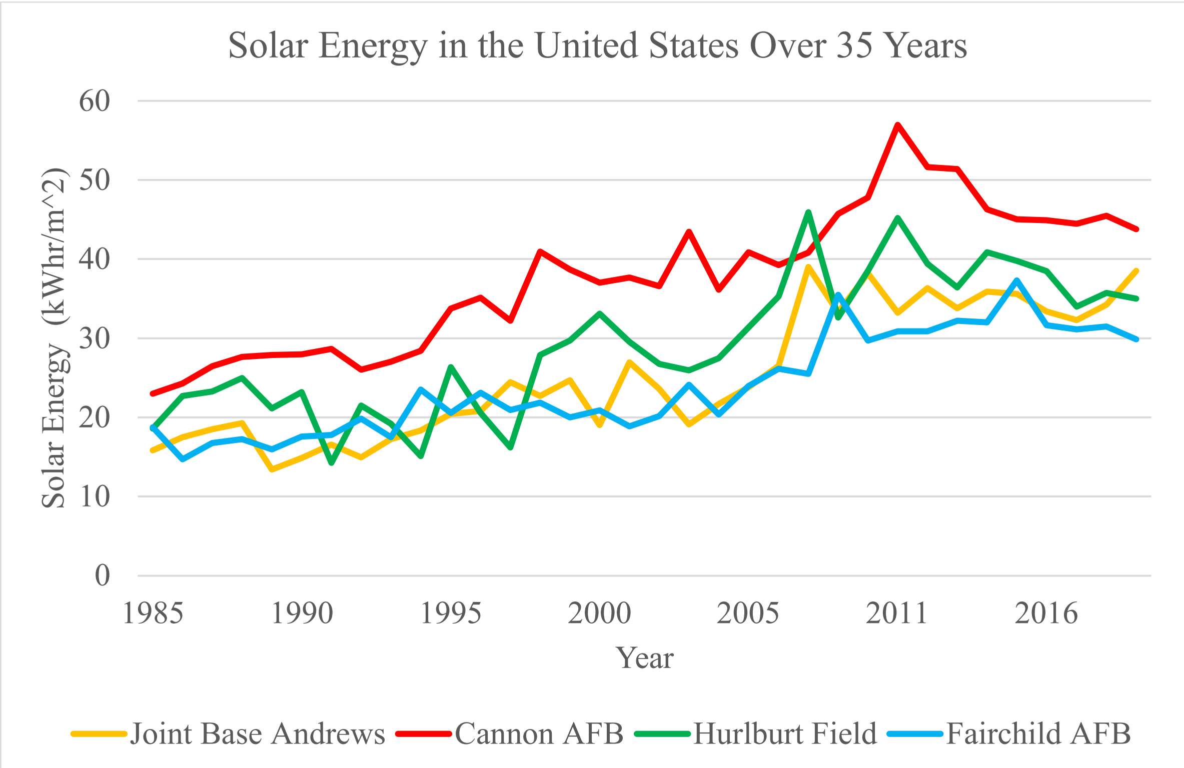


Figure 21 - Solar Energy (kWhr/m^2) from 1985-2019

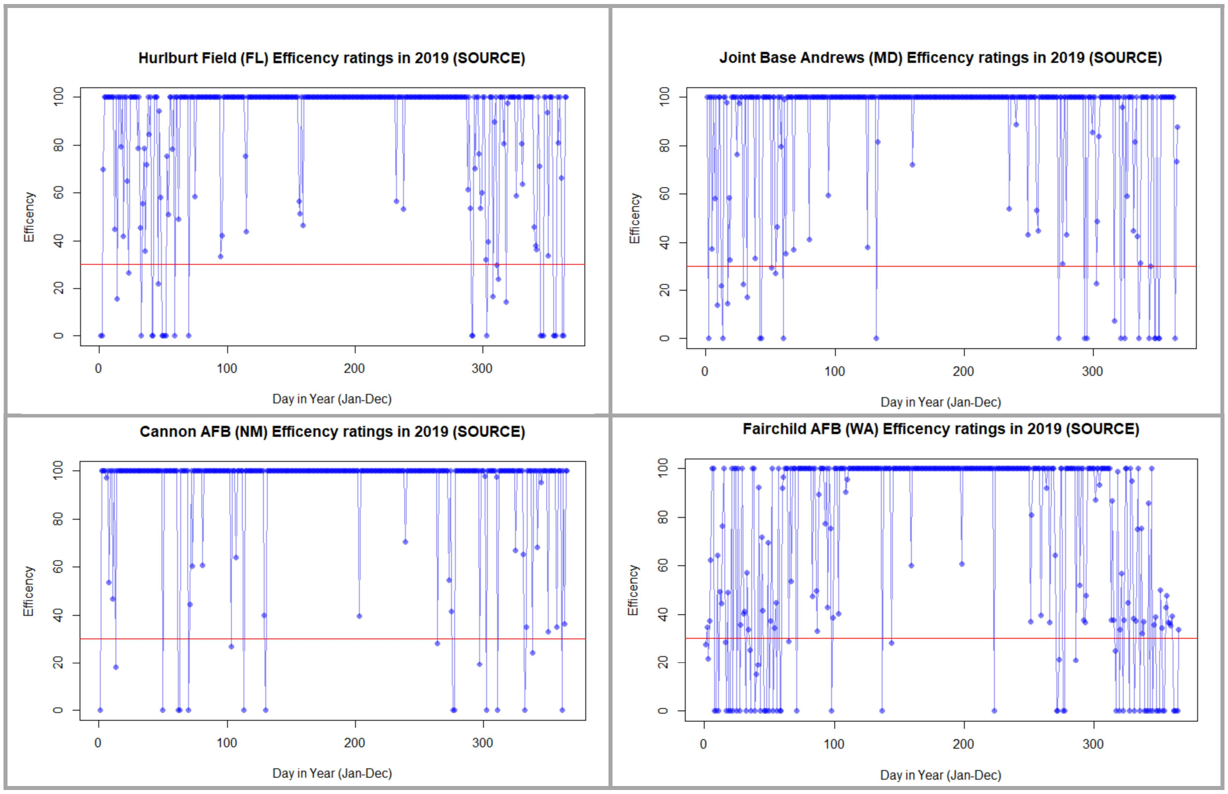


Figure 22 - SOURCE Daily Efficiency Data for 2019 at Case Study Locations

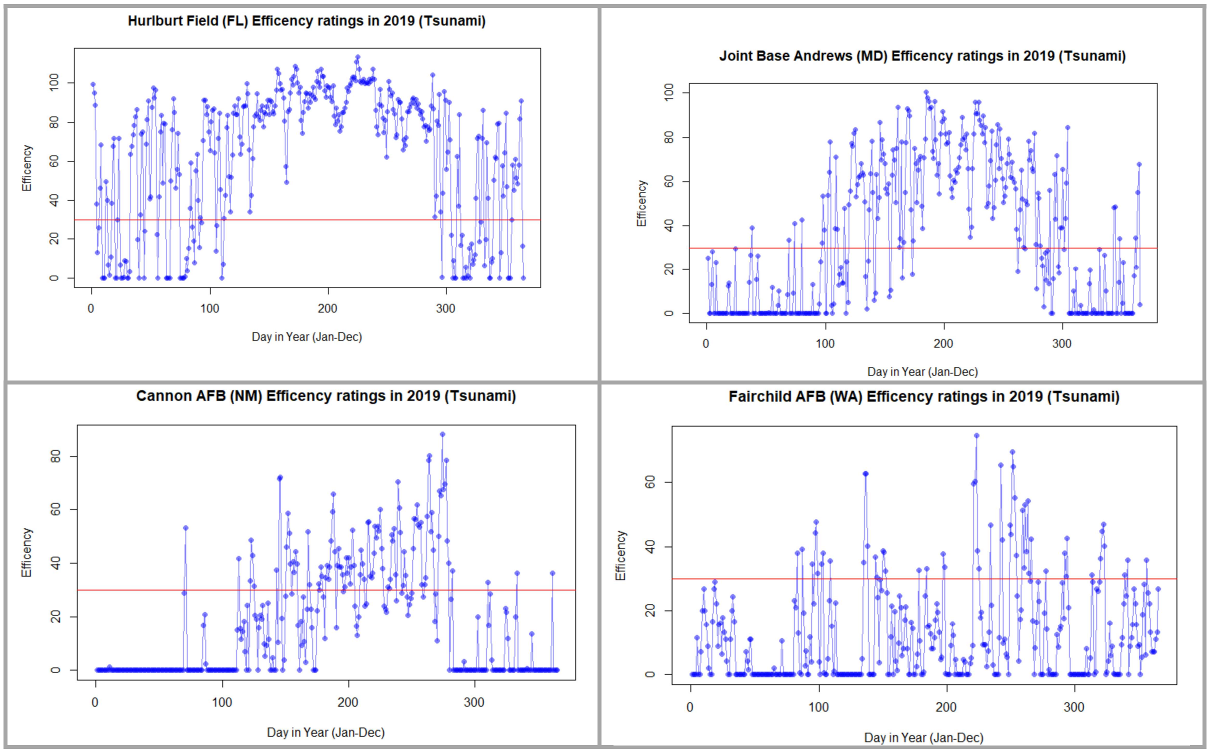


Figure 23 - Tsunami Daily Efficiency Data for 2019 at Case Study Locations

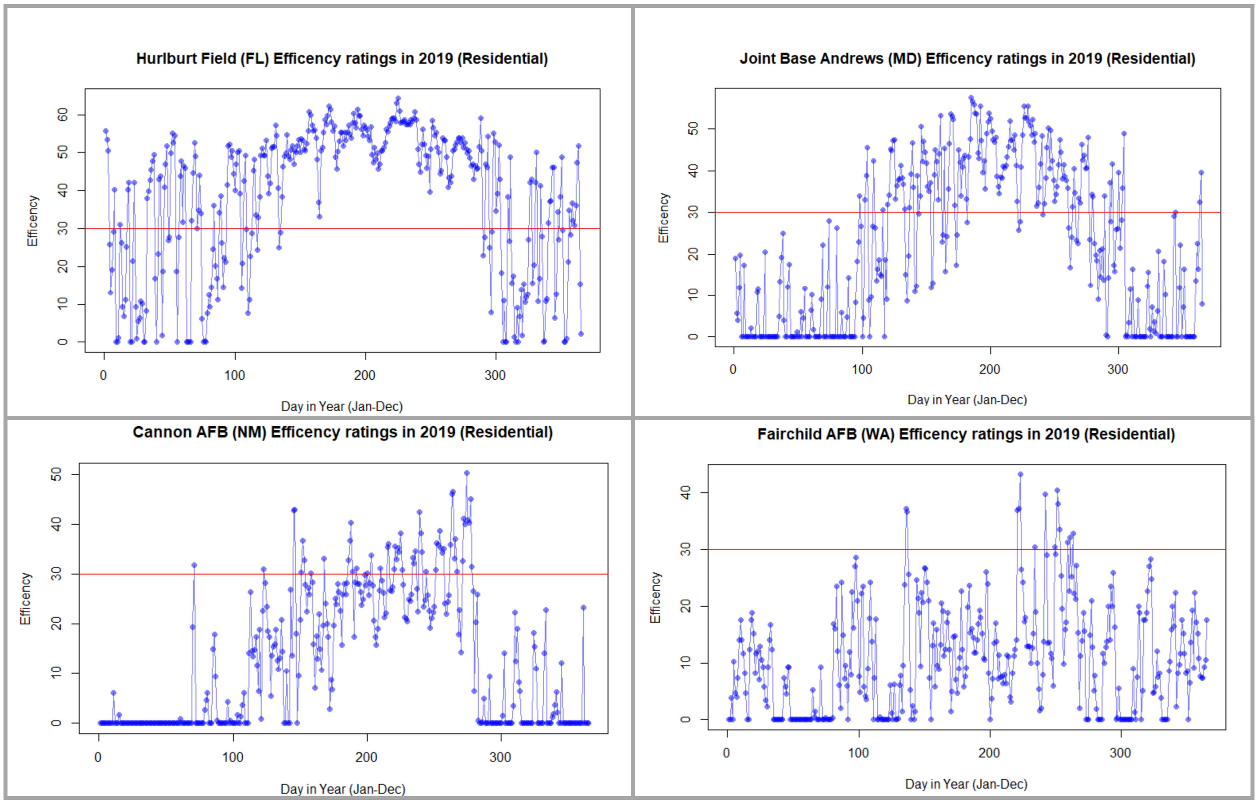


Figure 24 - Residential Daily Efficiency data for 2019 at Case Study Locations

Appendix B

```
Call:
lm(formula = liters.per.day ~ Avg.RH + Solar.Energy..kWhr.m.2.,
    data = source.data)

Residuals:
    Min      1Q  Median      3Q     Max
-0.4676 -0.1517  0.0362  0.1546  0.2905

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)             -2.738659   0.407786  -6.716 3.28e-07 ***
Avg.RH                   0.047429   0.002318  20.464  < 2e-16 ***
Solar.Energy..kWhr.m.2.  0.841230   0.067278  12.504 9.63e-13 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2168 on 27 degrees of freedom
Multiple R-squared:  0.9552,    Adjusted R-squared:  0.9518
F-statistic: 287.6 on 2 and 27 DF,  p-value: < 2.2e-16
```

Figure 25 - SOURCE Linear Model Summary

```
Call:
lm(formula = Water.Output ~ RH + Temperature, data = Tsunami)

Residuals:
     Min       1Q   Median       3Q      Max
-176.286  -78.376   -9.321   51.055  258.486

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -1716.0730   101.3334  -16.93   <2e-16 ***
RH             13.1371     0.7178   18.30   <2e-16 ***
Temperature    17.3966     1.0551   16.49   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 108.3 on 62 degrees of freedom
Multiple R-squared:  0.9073,    Adjusted R-squared:  0.9043
F-statistic: 303.4 on 2 and 62 DF,  p-value: < 2.2e-16
```

Figure 26 - Tsunami Linear Model Summary

```
Call:
lm(formula = Water.Harvesting.Rate ~ Temp + RH, data = Residential)

Residuals:
       1        2        3        4        5        6        7 
 0.06043  0.02476 -0.13357 -0.07759  0.07185  0.09925 -0.04513 

Coefficients:
             Estimate Std. Error t value Pr(>|t|)   
(Intercept) -0.835808   0.231492  -3.611  0.02255 * 
Temp         0.026592   0.005173   5.140  0.00679 **
RH           0.010123   0.002703   3.746  0.02002 * 
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1063 on 4 degrees of freedom
Multiple R-squared:  0.8713,    Adjusted R-squared:  0.807 
F-statistic: 13.54 on 2 and 4 DF,  p-value: 0.01656
```

Figure 27 - Residential Linear Model Summary

Appendix C

Table 4 - Source Observed Values

RH (%)	Solar Energy (kWhr/m^2)	Liters Per Day
20	5	2.5
30	5	3
40	5	3.5
50	5	4
60	5	4
70	5	4.5
20	5.41	3
30	5.41	3.5
40	5.41	4
50	5.41	4
60	5.41	4.5
70	5.41	5
20	5.83	3
30	5.83	3.5
40	5.83	4
50	5.83	4.5
60	5.83	5
70	5.83	5.5
20	6.25	3
30	6.25	4
40	6.25	4.5
50	6.25	5
60	6.25	5.5
70	6.25	6
20	6.66	3.5
30	6.66	4
40	6.66	5
50	6.66	5.5
60	6.66	6
70	6.66	6

Table 5 - Tsunami Observed Values

Temperature	RH (%)	Liters Per Day
104	0.3	311
104	0.35	391
104	0.4	468
104	0.45	553
104	0.5	637
104	0.55	811
104	0.6	979
104	0.65	1073
104	0.7	1159
104	0.75	1253
104	0.8	1343
104	0.85	1441
104	0.9	1534
95	0.3	238
95	0.35	298
95	0.4	355
95	0.45	422
95	0.5	486
95	0.55	620
95	0.6	748
95	0.65	818
95	0.7	884
95	0.75	957
95	0.8	1024
95	0.85	1101
95	0.9	1170
86	0.3	180
86	0.35	224
86	0.4	267
86	0.45	326
86	0.5	398
86	0.55	511
86	0.6	562
86	0.65	615
86	0.7	668
86	0.75	720

86	0.8	768
86	0.85	837
86	0.9	884
77	0.3	134
77	0.35	167
77	0.4	198
77	0.45	242
77	0.5	271
77	0.55	378
77	0.6	417
77	0.65	457
77	0.7	495
77	0.75	533
77	0.8	573
77	0.85	613
77	0.9	655
68	0.3	100
68	0.35	124
68	0.4	146
68	0.45	178
68	0.5	200
68	0.55	278
68	0.6	307
68	0.65	335
68	0.7	362
68	0.75	391
68	0.8	420
68	0.85	447
68	0.9	482

Table 6 - Residential Observed Values

Temperature	RH (%)	Liters Per Hour
30	62	0.65
20	75	0.48
6	80	0
32	20	0.14
21	45	0.25
6	57	0
25	50	0.29

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14. ABSTRACT

Atmospheric Water Generators (AWG) extract water from the air using one of three available technologies: refrigeration, sorption, and fog harvesting. A refrigeration device works like a dehumidifier and works best in conditions above 60% relative humidity. A sorption device utilizes a desiccant to extract the water vapor from the air and works in very low humidity levels. A fog harvesting device utilizes a mesh to capture the water vapor from the air and requires 100% relative humidity. In this research, I analyze two refrigeration-based devices and one sorption-based device and their efficacy in providing supplemental water supply. Due to climatological and technological constraints, not all regions in the world would see the same water production from an AWG as production is driven by high relative humidity and temperature. This climatological

reliance also subjects them to dramatic changes in performance depending on the season. By using previously established hydrologic performance indicators and weather data for the United States, I determine the year-round efficiency metrics of the typical residential-sized refrigeration AWG. Using these efficiency metrics, I also determined the reliability, resiliency, and vulnerability of the AWG to produce potable water seasonally across the United States. By evaluating several different devices and mapping the efficiency on the country-scale, this research determines the regional efficacy in adopting AWG technology to supplement potable water supply. This study was the first to look at the performance of atmospheric water generators with such granularity, as well as comparing specific devices predicted water production output to each other and over the years and calculating their Hashimoto's hydrological indicators.

15. SUBJECT TERMS

Atmospheric Water Generator, reliability, resiliency, vulnerability, hydrological indicators, sorption, fog harvesting, refrigeration, efficiency, spatial analysis

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