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RESEARCH ARTICLE

Benchmarks of production for atmospheric water generators in the United States

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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. In this research, we analyze two refrigeration-based devices and one sorption-based device and their efficacy in providing supplemental water supply across the United States. An AWG can supply potable water to remote and austere locations where clean drinking water might otherwise be unavailable. With increasing water scarcity globally, particularly in historically arid climates, new methods that can draw from an estimated 13,000 km^3 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 (reliability, resilience, and vulnerability) and weather data for the United States, we determine the year-round efficiency metrics of three AWGs. By evaluating three different devices and mapping the efficiency across the United States, this research determines the regional efficacy, as a function of water production, in adopting AWG technology to supplement potable water supply. This study provides important insights into the performance of AWGs with high spatial resolution through comparison of multiple devices. The results indicate minimal viability for a large portion of the United States. However, we highlight the potential for the device to supply water for a remote military installation in Hawaii.

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1 Introduction

Water scarcity threatens human survival and hygiene and access to potable water is highly variable across the globe. Water access is both a function of climatological variables and societal or governance issues with rural communities being far away from the more urban water sources or lack of government planning to facilitate equitable access of water [1–3]. An estimated 4 billion people face water scarcity at least one month in a year [4]. The atmosphere is filled with an estimated 13,000 km^3 of water [5]. Conventional water sources are not always available, therefore it is important to investigate alternative sources of water. Alternative

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technologies to potentially solve water scarcity in areas with limited access are becoming increasingly available and affordable, with many studies evaluating the optimal reliability or preferred portfolios of these alternative studies in water stressed environments [6–10]. Alternative water sources include direct water reuse [11–13], grey water recycling [14], rainwater harvesting [14], and desalination [9, 15, 16].

However, many of the more prevalent technologies require significant permanent infrastructure and do not account for remote or temporary conditions. One such alternative water supply for these conditions are atmospheric water generators (AWG). AWGs offer a means to extract water from the local atmosphere for potable uses. An AWG can also be combined with solar power generation making it a completely standalone system [3]. This research investigates the feasibility of current AWG technologies based on seasonal changes and varying climates, simulated using historical data. These 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, which are especially important in rural and austere locations with minimal existing water infrastructure.

In some areas, alternative technologies such as ceramic pots, reverse osmosis treatment, or rainwater capture are deployed, but they still rely on an existing surface or groundwater supply. Ceramic pots, used in some remote locations, are porous materials that remove most of the impurities found in water, specifically ceramic pots imbedded with silver are even more effective [17]. 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 [18]. A reverse osmosis system also comes with brine that requires proper disposal, at as much as a 1:1 ratio with usable water. This brine can have deleterious effects on the environment and surrounding wildlife depending on its concentration. There has been research into creating more efficient RO systems, such as one that recirculates water, however cost and maintenance requirements are somewhat prohibitive [19]. 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 dependent on favorable weather patterns [20].

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 [21]. This is largely due to its current inefficiency and scalability concerns. In general, an atmospheric water generator system must meet several criteria to be considered a viable solution, including affordability, scalability, and stability to provide a reliable water volume throughout the year [21]. As AWGs are highly dependent on weather, seasonal weather fluctuations pose one of the largest threats to AWGs use as a consistent water supply.

Therefore, we focus primarily on the stability aspect of AWGs. Utilizing 35 years of historical weather data from 1985–2019 across the United States, we analyze the theoretical performance of three different, current, commercial AWG technologies. We utilize existing metrics of reliability, resiliency, and vulnerability from Hashimoto et al. [22] to understand the temporal and spatial dependencies of these technologies, normalized against the efficiency of each technology. Through the analysis we make recommendations on the current state of the technologies to provide a stable water supply and highlight some opportunities of the technology in remote environments with limited existing infrastructure. Previous studies of AWG viability have investigated global theoretical availability [23] but have minimal investigations as the sub-annual scale and lack an understanding of interannual variability. We build on this previous research using empirical performance data from the technologies to understand changes in the stability of the technology across multiple years.

2 Technology and device selection

2.1 Atmospheric water generation

Atmospheric Water Generators (AWG) use one of three different methods to generate potable water from the air: fog harvesting, active refrigeration, and sorption [24]. Fog harvesting uses a mesh device to increase water condensation and requires 100% relative humidity. Sorption uses a desiccant to separate the water vapor from the air, which can be used in relative humidity levels as low as 20%. The final method, and the most commercially available, is active refrigeration. Active refrigeration devices force atmospheric water to condensate by cooling the air below the dew point temperature, the same process as a dehumidifier with the addition that an AWG also makes the water potable [25].

Fog harvesting typically utilizes a mesh device and requires 100% relative humidity to function [24]. 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 [21]. The biggest issues with this method are its reliance on high humidity and the mesh's tendency to get clogged [21]. Examples of fog harvesting can be found across the globe with successful implementation in Chile [26], Morocco [27], and elsewhere [28, 29].

The sorption method of atmospheric water harvesting utilizes a desiccant to separate the water vapor from the air [24]. This technology can be used in very low relative humidity levels and is typically paired with solar photovoltaic power. Therefore, it can function completely off the grid and is usually very mobile. However, the trade-off for this mobility is that, out of the three methods, a single sorption based unit produces a much smaller quantity of water. Additionally, based on current technologies, costs are relatively high for the volume of produced water. Li et al. [24] created a form of hydrogel with deliquescent salt embedded inside the hydrogel with 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. Currently the Defense Advanced Research Projects Agency (DARPA) is interested in further applications of sorption methods for larger scale uses [30].

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 [24]. 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. In two different studies by Joshi et al. [31] and Shourideh et al. [3] the refrigeration method was evaluated based on the water production rate relative to environmental factors. Those variables are the air flow velocity, the relative humidity, and the power supply, highlighting these factors as the constraints 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 compared to the same temperature. The drawback of increased air flow, however, is an increased energy demand.

2.2 Device selection

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 integrated solar panel. The other two devices, Tsunami, and an anonymous residential device, henceforth known as residential, use refrigeration, which is the most common method for commercially available devices. Both the SOURCE and Tsunami devices are commercially available systems.

The third device remains anonymous as its functionality is based on a previously published peer-reviewed article with data that excludes the manufacturer of the device from its report. Devices were selected based on data availability and water production.

Using data from the technical specifications documentation of the SOURCE panel [32], the technology collects water vapor from the air onto a hygroscopic material, then, with the heat from the sun, 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 1.2 x 2.4 x 1.1 meters and weighs around 154 kg. Its optimum operating conditions are from 1 to 55 degrees Celsius and from 10 to 100% relative humidity. Each panel can produce between two to five liters of water per day. The 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 When placed in an array each panel needs to have at least 1.2 meters of clearance in front and behind the device, but they can be placed adjacent to each other on the sides.

The second device evaluated is the commercial refrigeration device from Tsunami. Device information was found on their technical worksheets and in conversations with representatives [33]. Water is drawn 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, working the same as those 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. The Tsunami company has several different sized devices, the one utilized in this research is the Tsunami-500 with dimensions of 1.1 x 1.1 x 2.3 meters and weighs 380 kg. The chosen model 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 1 meter clearance around the perimeter and at least 4.6 m of clearance above to function efficiently. As stated by the manufacturer this device works best between 15 degrees latitude above and below the equator.

The final device evaluated is an anonymous refrigeration device for residential use based off of laboratory results from Bagheri et al. [25]. The study investigated the performance indices of three residential devices that utilize refrigeration within an enclosure that regulated both the temperature and relative humidity. The three unnamed residential sized devices, all with an optimal maximum output of 30 liters of water per day, were tested under seven varying conditions. The conditions ranged from warm and humid to cold and dry. For this research the results from the first residential device discussed within the article were utilized.

3 Materials and methods

3.1 Data gathering

To evaluate the AWGs at this scale, a large amount of data had to be gathered, including both historical weather data and performance measures of the different AWG technologies. The performance data for each of the three AWG devices were collected from either the commercial technologies' performance sheets [32, 33] or, in the case of the anonymous residential device from Bagheri et al. [25]. Relevant performance data included treated water output against different weather condition. The SOURCE device had 30 measured treated water outputs against relative humidity and solar energy, due to its embedded PV solar panel. The selected Tsunami device had 65 analyzed treated water outputs against relative humidity and temperature. However, per the Bagheri et al. [25] study, only seven combinations of humidity and temperature were analyzed and reported for the residential device. The limited sample size of the final device does pose some concerns for the viability of the model. However, we elected to include the small sample to compare lab-tested results against technical reports produced by the manufacturer.

Weather data was obtained from AccuWeather, which collects data from a variety of sources including the National Weather Service, National Oceanic and Atmospheric Administration, among others. These data spanned 1,935 stations across the United States for 35 years, with daily average weather [34]. Variables included within the analysis are weather station code and location, date, 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.

3.2 Model building

Multivariate linear regression models were generated for each device to predict the daily volume of water produced. These linear models can be seen in Eqs 1–3. β_0 is the intercept and β_1, β_2, and β_3 are the constants for temperature, relative humidity, and solar irradiance, respectively.

$$SOURCE\ Daily\ Water\ Havesting\ Rate = -\beta_{0a} + \beta_{2a} * RH + \beta_{3a} * S \tag{1}$$

$$Tsunami\ Daily\ Water\ Harvesting\ Rate = -\beta_{0b} + \beta_{1b} * T_F + \beta_{2b} * RH \tag{2}$$

$$Residential\ Hourly\ Water\ Harvesting\ Rate = -\beta_{0c} + \beta_{1c} * T_c + B\beta_{2c} * RH \tag{3}$$

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 irradiance (kWh/m^2), and all harvesting rates are reported in liters. The independent variables for each model were chosen based on the manufacturer specifications for production as a function of climate variables. The sorption device, SOURCE, specifies output based on solar irradiance and relative humidity, see S1 Fig. However, the two refrigeration devices describe water production as a function of temperature and relative humidity. We recognize potential bias associated with using different independent variables and manufacturer specifications in the results. However, individual testing of each device was outside the scope of the empirical study.

Each linear regression model for the different devices was checked for normality and constant variance. The Shapiro-Wilks test was used for residual normality and the Breusch-Pagan test for constant variance. Additionally, each model was validated using a k-folds cross validation.

3.3 Reliability, vulnerability, and resilience

Due to the different maximum capacities of each device output was normalized to an efficiency before any benchmarking or comparison could be made. Efficiency rate is defined as the relative output against the maximum daily harvesting rate of atmospheric water. Maximum harvesting rates are 6 Liters, 773 L, and 30 L for the SOURCE, Tsunami, and residential device, respectively. For example, 3 L of output for the SOURCE device would be 50% efficiency, but only 0.3% for Tsunami and 10% for the residential device. Therefore, it was necessary to normalize across some uniform benchmark to facilitate comparison. Daily outputs from each device were calculated across all years of weather data for each station. For each device, average daily values from the same day were used to estimate production. As the sorption device requires a staged process for atmospheric water capture and then released from the material, there is potentially some bias in using relative humidity and solar irradiance values from the same day as there could be sudden changes between days, limiting its efficiency. However, as the metrics are reported and averaged over a 35 year time-scale, this bias and variability is largely balanced out by average climate at each station.

Hashimoto et al. [22] presented three metrics for water resource system performance evaluation. Reliability represents how often the system is in a successful state. Resiliency calculates how quickly the system recovers after a failure has occurred. Vulnerability, as described in the metric, is the degree of failure or magnitude failure. Without knowing the application of the device it is difficult to understand the consequence of the failure, which is another standard for vulnerability. By, instead, looking at the degree the device fails the results can be more broadly interpreted before being applied to a specific scenario. Each of these three benchmarks are required to fully discuss the stability of the devices. However, to assess each of these metrics, a standard of failure is required. The establishment of the failure metric has impact on the results. We defined a failure as below 30% efficiency and a success as anything greater. This threshold was selected based on the different efficiencies between devices as well as seasonal fluctuations. While this threshold might be somewhat conservative, it is a necessary assumption for analysis. A higher threshold will limit comparability between the two technology types as the sorption has a much higher efficiency overall. However, too low of a threshold will inflate the results. Decision-makers will need to select their level of efficiency for failure based on water demand and storage as well as cost considerations.

For an AWG, reliability is defined as the probability the device is in a successful state at any given time step (daily). Reliability was calculated annually and for each quarter suing Eq 4.

$$Reliability\ \% = \frac{n_S}{N} * 100\% \tag{4}$$

Where n_s is the number of days in a successful state in a given period of length, N. A 0% reliability references a technology that never left a failure state during the observed period, while a 100% reliability means that the technology never entered a failing state.

Resiliency is the probability that, given a previous failure, the next time step is in a successful state. In other words, if the current day is a failure state, what is the probability that the next day will be a success? This calculation is represented by Eq 5.

$$Resiliency\ \% = \frac{S_t|F_{t-1}}{n_f} * 100\% \tag{5}$$

Where S_t is a successful state in time, t, F_{t-1} is a failure state in in the previous time step, $t-1$, and n_f is the number of failure events. If reliability is 100%, signifying there is no failure state, resiliency is undefined. A 100% resilience state would have every failure state succeeded by a success. In other words, there would be no consecutive days of failure.

We define vulnerability as the maximum of the average failure state across each grouping of failures. Across the time period of interest, consecutive failures stages are grouped together and then averaged. The maximum value of these averages is then reported as the vulnerability. Depending on the season and device this created anywhere from 1 to 20 different vulnerability groupings. Vulnerability is calculated in units of liters, representing an average deficiency from the failure threshold of each device. This metric is further normalized to account for the differences in maximum total production. The SOURCE and residential technologies were normalized to the larger capacity of the Tsunami technology using scaling factors, 129 and 26, respectively. Decision-makers should assess future vulnerability based on the consequence of the degree of failure through an assessment of demand and storage, which is outside the scope of the study.

3.4 Spatial analysis

Spatial representations of the data were represented at the county scale across the United States to avoid data gaps. Weather stations within 80 km of each county were averaged and assigned to each county. This assumption of 80 km was needed to provide a smoothed surface across a majority of the counties in the United States. Not all counties in the United States contained a weather station in the dataset, and, therefore, interpolation was necessary. A spatial join was used in ESRI ArcMap v10.8 to perform the analysis.

4 Results and analysis

4.1 Linear model results

The results from the linear models and their requisite tests can be found in Table 1. A significance value of 0.05 was assumed for all tests. For the Shapiro-Wilks test for residual normality, all tests failed to reject the null hypothesis that the residuals are normal. The Breusch Pagan test for constant variance also fails to reject the null hypothesis that the residuals have constant variance. Validation of the model was completed with a k-folds cross validation (CV) with five groups. Comparing the residual standard errors between the original model and cross validated model shows minimal variations between the SOURCE and Tsunami models. The residential device had minimal data points and therefore shows a significant difference in error when validating. However, in all we are confident in the linear models capturing most of the variability of our data, recognizing the current data limitations of the AWG technologies' performance.

4.2 Seasonal efficiency analysis

Fig 1 shows the spatial efficiency in each quarter for each device for the year 2019. The year 2019 is illustrated to show the most recent year of data available and the inter-annual comparisons will be further discussed at four locations. Quarters of the year are defined as three month sequences with January- March in Quarter 1, April-June in Quarter 2, etc. The SOURCE device has the highest overall efficiency of any device across all quarters. As the SOURCE panel utilizes a sorption technology, the higher efficiency is due to its ability to work in lower relative humidity levels. Therefore, in arid climates, such as the Southwestern United States, characterized by hot and dry climates, the SOURCE panel outperforms the refrigeration devices, from an efficiency perspective, albeit with a low output. As the SOURCE technology uses solar irradiation instead of temperature to determine its water output per day, it is impacted by locations that either have lower solar availability from season-to-season, such as

Table 1. Results of the linear models show high amounts of variance explained with cross validation results indicating for the SOURCE and Tsunami devices a high degree of certainty in prediction.

Value	SOURCE	Tsunami	Residential
β_0	-2.74	-1720	-0.836
β_1 (Temperature)	NA	17.4	0.0266
β_2 (Relative Humidity)	0.0474	13.1	0.010
β_3 (Solar Irradiance)	0.841	NA	NA
Model R^2	0.95	0.90	0.81
Shapiro-Wilks (P-value)	0.18	0.07	0.65
Breusch Pagan (P-value)	0.29	0.30	0.15
Residual Standard Error	0.22	108.3	0.08
K-folds CV (RMSE)	0.22	108.6	0.15

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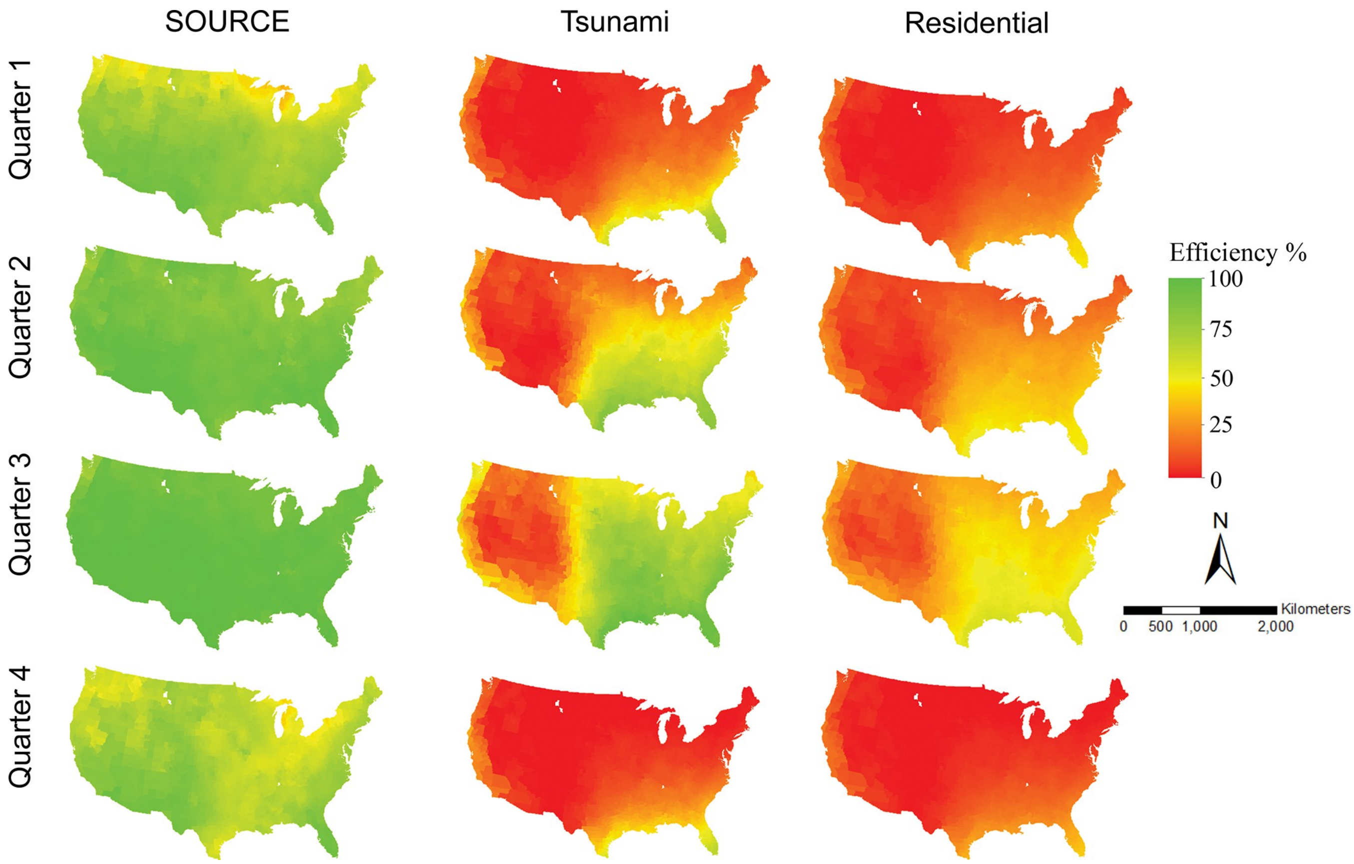

Fig 1. The viability of each of the refrigeration devices (Tsunami and Residential) is highly variable across the country and between the seasonal quarters. The SOURCE technology has a more consistent performance, spatially and temporally, with lowest outputs in the fourth quarter of the year. Base maps of the United States are from the U.S. Census Bureau [35].

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the northern latitudes in the winter. All calculations for the SOURCE device were performed at the daily scale, meaning that there is some uncertainty in actual output due to solar availability coinciding with generally drier air in the day.

Investigating the refrigeration devices shows an increase in efficiency during Quarters 2 and 3. Particularly this trend is evident in the southeastern United States. In the warmer and more humid climates, like Florida and Georgia, the Tsunami AWG has as much as a 95% efficiency in some areas. Lastly the Residential device shows the worst overall efficiency. The device only reached a maximum of 60% efficiency in the best-case scenario, 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.

4.3 Inter-annual comparison

In addition to seasonal evaluations, we investigated performance at the annual scale utilizing the average annual efficiency and reliability/resilience benchmarks for assessment. Annual assessments from 1985 to 2019 are shown on Fig 2 for four different locations. The four example locations are Department of Defense installations from various climates: (1) Joint Base Andrews, Maryland, in the Middle Atlantic region; (2) Hurlburt Field, Florida, on the Gulf of Mexico; (3) Fairchild Air Force Base, Washington, in the Northwestern United States; and (4) Cannon Air Force Base, New Mexico, in the Southwestern United States. These four locations

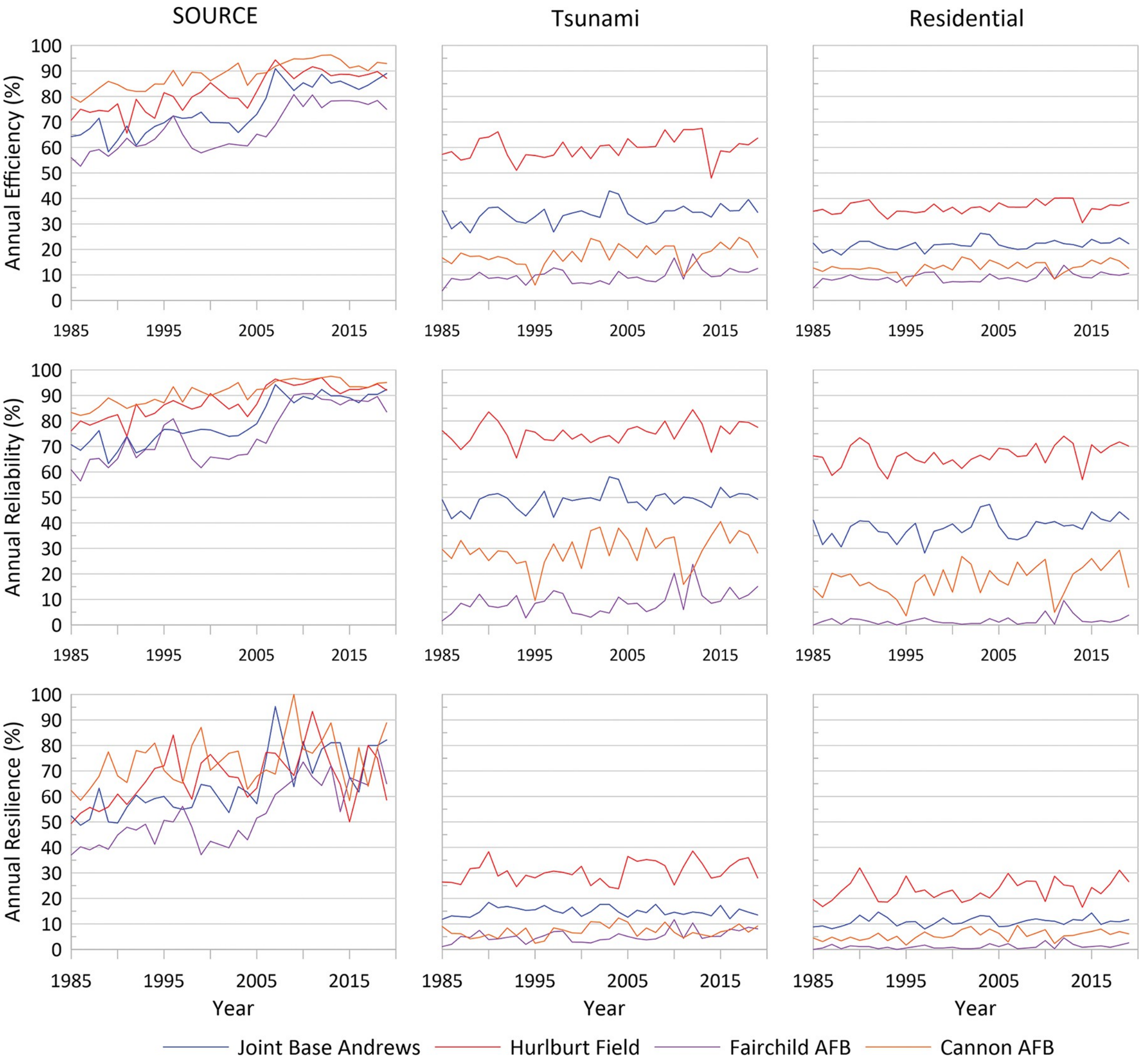

Fig 2. Inter-annual fluctuations of benchmarks show minimal change over time for the refrigeration device but increase for the SOURCE technology.

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represent different climates and regions of the United States. Additionally, the selection of military installations for the case studies aligns with a possible use of the devices in a contingency or austere environment often navigated by the Department of Defense. However, the methods provided within the article can be generalized to any location across the United States to assess the stability of the devices in each environment.

In general the SOURCE panel has a slight increase over time in all metrics (efficiency, reliability, and resilience) for each of the four locations. Both the Tsunami and Residential devices vary without any consistent trend across the years. In general Hurlburt Field in the panhandle of Florida along the Gulf Coast has the highest performance in both efficiency, reliability, and resilience for all four locations using the refrigeration devices. Between the four locations and the refrigeration devices, the same order of performance exists. Resilience for all devices hovers between 0 and 40%, signifying that there is minimal recovery back to a success threshold after a failure.

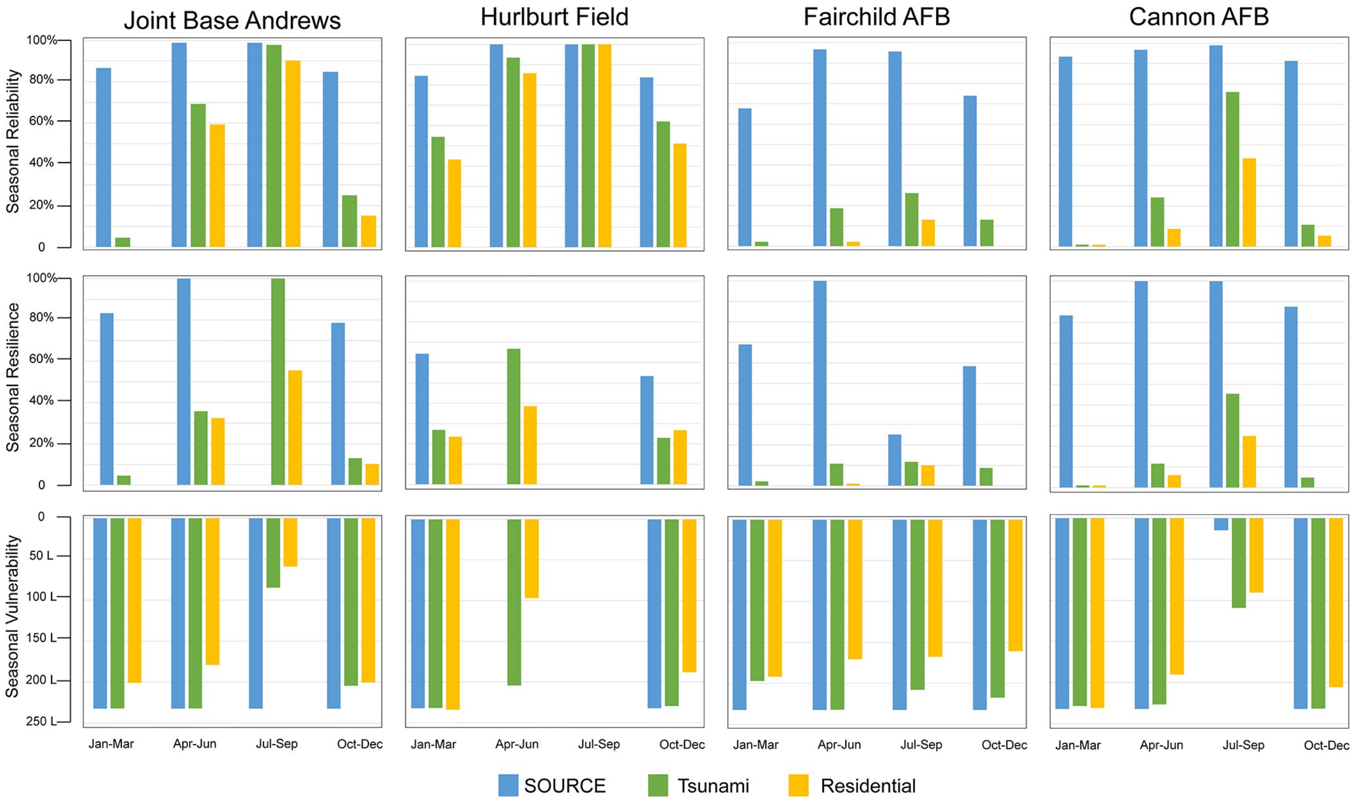

Fig 3. The combination of all three metrics offer opportunities to investigate the suitability of atmospheric water generators across seasons and locations.

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4.4 Seasonal device comparison

Continuing to use the four locations as our case study, we investigate seasonal averages of the reliability, resiliency, and vulnerability benchmarks. Fig 3 show the seasonal changes of each device at the four locations. A device with no shown resilience and no corresponding vulnerability indicates a 100% reliable technology, such as Quarter 3 at Hurlburt Field. As expected from the efficiency map (Fig 1) the SOURCE device has the best reliability and resiliency followed by the Tsunami 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. While reliability of the SOURCE panel is generally high across all locations and seasons, when it does fail, it has significant vulnerability or liters deficient. 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. In general, most of the devices and locations show high vulnerability indicating that these technologies are not suitable as a singular source of water across the year for day-to-day consumption.

5 Discussion

Using metrics of efficiency, reliability, resilience, and vulnerability we investigated three different atmospheric water generating technologies spatially and temporally. Of the three devices investigated, two were refrigeration and one was a sorption-based technology. The sorption-based technology performed the most consistently across the year and the country. However, this comes at a cost, sorption devices, based on current research, produce far less quantities of water than the other two methods and, at current levels, are more costly. So, while it is more efficient, it still might not be the best device depending on its intended use due low outputs. Due to the reliance all atmospheric water generators have on the weather, the performance of the AWG will vary greatly throughout the Unites States and between seasons. This is especially evident in refrigeration devices (Figs 1–3).

The resiliency of each device follows the same trend as their reliability. The SOURCE device performs the best in each location and season. 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. This occurred for all four case study locations in every season. Meanwhile the Tsunami device still produced some water even when they were in a failure state. 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 weather data, solar irradiance shows a significant increase over the years. 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.

While the widespread application of the technology of the United States is called into question in the analysis, we acknowledge some potential uses of the technology. As an example, the 611th Civil Engineering Squadron (CES) of the United States Air Force operates several remote locations across the Pacific Ocean. Specifically, two of those locations are in Hawaii. One of these locations is located over 1000 meters above sea level and is currently without a permanent potable water solution. Water has been brought in barrels to serve the minimal population at the locations ($<$ 30 persons). Additionally, manning is regularly fewer than 10 persons, reducing the daily requirement of water consumption to approximately 2500 Liters per day. Based on the current state of the infrastructure and the minimal personnel requirements, refrigeration-based AWGs would be a suitable and reliable alternative. Fig 4 illustrates the annual refrigeration efficiency of the Tsunami device in Hawaii. With its warm and moist climate, the location is ideally suited to employ this type of non-traditional potable water system. Other possible applications include recovering from natural disasters in warm-humid climates such as Southeastern Asia or the Caribbean islands. These portable devices could be transported as part of aid packages to provide reliable drinking water to these climates with minimal associated infrastructure.

This study shows the variability, both spatially and temporally, of the three devices across the United States using four benchmarks: efficiency, reliability, resilience, and vulnerability. However, the study has some limitations regarding its formulation. First, the selection of a

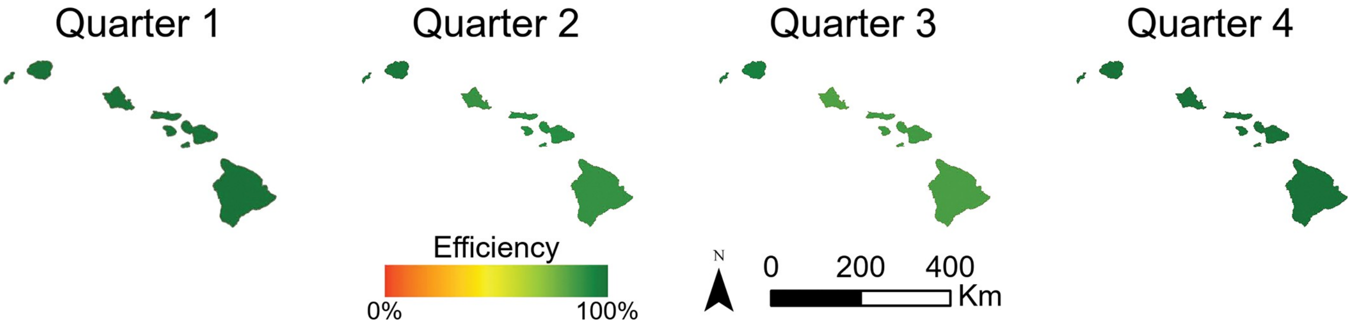

Fig 4. Efficiency in Hawaii for the Tsunami device is consistently high throughout the year. Base maps of the United States are from the U.S. Census Bureau [35].

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30% efficiency benchmark for failure induces some bias in the other three metrics. However, these metrics all require some defined threshold of failure to calculate. A higher efficiency threshold would reduce both the reliability and resilience of most of the advices, as well as increase the vulnerability. The 30% threshold was chosen as it provides a relatively even benchmark across all of the three devices to facilitate comparison. Refinement of this failure status could include considerations of storage analysis or demand. Another limitation is the anonymous refrigeration device from Bagheri et al. [25], which limits potential validation of the results.

Finally, the presented benchmarks for water production are not the only parameters needed in making a feasibility decision for the technology. There are several other benchmarks that could be used in the analysis including cost, energy-efficiency, scalability, operational ease, or portability. Modelling cost or affordability is likely chief among these considerations and is a function of the technology acquisition costs, energy inputs for refrigeration device, and maintenance costs. However, the calculation of these benchmarks are outside the scope of the current study, which focuses on water production benchmarks. We reserve these indicators for future work, focusing on the spatial and temporal variability of the three devices as illustrated by the indicators from Hashimoto et al. [22].

6 Conclusions

There is a large variance in how well atmospheric water generators performs in the United States given the different seasons and climate zones. However, the SOURCE device is as much as two times more efficient than the two refrigeration devices for much of the contiguous United States. The seasonal variation of the refrigeration method ranges from 0% to 98% reliability at Joint Base Andrews in the Middle Atlantic region alone, makes a refrigeration-based AWG an unreliable source of water generation for the contiguous United States. The increased efficiency, however comes at a cost of both low water volume output per unit and monetary cost.

The sorption method can be seen with an average efficiency above 70% year-round at all locations, but the quantity of water produced per device is very low requiring a large number of devices for even small groups of people. Based on our analysis of reliability, resilience, and vulnerability benchmarks, AWG are not suited to be stand-alone sources of water for much of the year throughout the United States. One exception to this trend are potential remote or austere sites in Hawaii or other tropical locations throughout the globe, such as other island or tropical communities recovering from a natural disaster. In Hawaii a refrigeration device sees on average above 40% efficiency for a standard device and above 60% efficiency for an advanced device year-round. This increase in efficiency is accompanied with enhanced reliability and reduced vulnerability of the technology, making it a more viable solution to remote water requirements.

Most devices that produce potable water like the ROWPU (reverse osmosis water purification unit) require a body of water nearby or ground water to draw from. In some areas, however, there might not be a feasible withdrawal location. 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 small numbers of people. Some remote or austere working locations are often supplied through cases of water bottles, which could be mitigate with AWGs in certain instances. Additionally, AWGs can be deployed in cases of a natural disaster to provide much needed water without the requirement of built infrastructure. While this study focused on stability of the technologies across different temporal and spatial scales, future research should investigate the remaining two metrics stated previously: affordability and scalability. These remaining metrics will further help decision-makers identify appropriate cases for use of the AWG technologies.

Supporting information

S1 Fig. SOURCE Hydropanel production. Daily Production for the SOURCE Hydropanel is a function of Relative Humidity and Solar Energy and is derived from manufacturer specifications.
(TIF)

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E.S. collected the data and performed the analysis. C.M.C conceived the study. C.M.C. and E.M. supervised the study and directed the research. All authors contributed towards writing the article.

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