3-2021

Water Security at United States Air Force Installations

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WATER SECURITY AT UNITED STATES AIR FORCE INSTALLATIONS

THESIS

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AFIT-ENV-MS-21-M-258

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

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Wright-Patterson Air Force Base, Ohio

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AFIT-ENV-MS-21-M-258

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

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March 2021

AFIT-ENV-MS-21-M-258

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AFIT-ENV-MS-21-M-258

Abstract

Global water security is a growing concern that poses unique challenges that stem from geopolitical arrangement, regional location, and local climate conditions. United States national defense relies on an uninterrupted water supply to sustain operations to carry out its readiness mission. Accurate water security assessments are necessary for adapting to climate factors and to provide essential information to meet the changing needs of human water demand. This research presents how different water metrics are applied at various United States Air Force locations to measure water scarcity. Geographical Information Systems (GIS) software is used to conduct spatial correlation across the United States to identify ranges between the metrics.

Reported water condition data from 34 United States Air Force installation development plans was assessed for correlation with the selected water scarcity metrics, though no evidence suggesting a relationship between the developed water scarcity index and the installation development plan data was identified. The development of an index to accurately relay water scarcity conditions will improve the ability to overcome water planning and regional water management challenges and combat factors that contribute to water scarcity. Such measures are needed to ensure water security as United States water resources face challenges from climatic variation and the threat of cyber-attacks on water systems.

Acknowledgments

I would like to express sincere appreciation to my wife and our children for their steadfast support and grounding as I pursued academic accomplishment under particularly challenging circumstances. To my faculty advisor, Dr. Christopher M. Chini, as his guidance, expertise and encouragement were essential in finalizing my thesis product. Without his unwavering professional support I would have never finished. I would like to thank my fellow students in the GEM program for their encouragement and voices of reason during a rigorous academic slate amid challenges that accompanied a global pandemic and created an isolating, virtual learning experience.

John D. Pollock

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WATER SECURITY AT UNITED STATES AIR FORCE INSTALLATIONS

I. Introduction

1.1 Background

Global tensions driven by uncertainty on the world's geopolitical climate have caused the United States Military to place renewed emphasis on readiness and mission capability. Military leaders use training metrics as a measure to assess preparation levels in these two areas. This is a prime example of one way metrics are used in the United States military. Another tactic to apply metrics in the United States military would be using them to measure water security. While water considerations may dwarf in comparison to larger geopolitical issues, a reliable water supply is critical to national defense as water is essential to the function of all Department of Defense (DOD) in-garrison mission-critical and support activities. Therefore, water security must remain a top priority[1]. Failing to adopt sound strategies aimed at mitigating water scarcity may force missions to delay, alter, or relocate carrying both steep fiscal costs and impeding the readiness interests of United States warfighting capability.

A recent study on integrating uncertainty into water resource planning concluded that significant gaps exist in planning to address climate-related impacts[2]. Key findings of the analysis showed that:

- only four percent of states have a strategy for addressing variability and uncertainty
- 70 percent of states lack any guidance on the impact of climate change
- floodplain mapping data used by the Federal Emergency Management Association (FEMA) was deem chronically outdated

Perhaps most concerning from a planners' perspective was that across the United States, drought planning guidance allocation was 94 percent for emergency response and the remainder for mitigation and management[2]. Compounding these findings with the United States Air Force's (USAF) increased reliance on local municipal organizations for water introduces risk by surrendering this responsibility. Though municipal suppliers are invested in meeting needs of their customer base, adding the volatility climate change introduces to weather patterns creates challenges for those tasked with water resource management decision making[2]. A question remains how water resource planners will develop sound plans to meet future water needs if their location is verified at-risk.

Limitations of water resources could leave the United States Military, namely the USAF ascending to meet adversaries in a position of superiority on the contested platforms monitored today. It is vital that the DOD and the USAF dedicate resources to counter future water security risks to ensure complete mission capability to prevent falling behind near peer military adversaries. The following research offers understanding of water resource conditions at USAF installations, and highlights the under-valued concerns of current water security methods.

1.2 Problem Statement

United States Air Force installations receive water from ground, reservoir, and flowing river and stream sources. Resource competition from domestic, industrial and agricultural consumers will remain despite measurable reductions in withdrawals in every sector over the last 20 years (Figure 1)[3].

	1998-2002		2003-2007		2008-2012		2013-2017	
Agricultural water withdrawal *(10^9 m3/year)*	194.7I	*(2002)*	185.2I	*(2007)*	175.5I	*(2012)*	176.2I	*(2017)*
Industrial water withdrawal *(km^3/year or $10^9 m^3$/year)*	301.3I	*(2002)*	282.4I	*(2007)*	232.9I	*(2012)*	209.7I	*(2017)*
Municipal water withdrawal *(km^3/year or $10^9 m^3$/year)*	64.58I	*(2002)*	64.1I	*(2007)*	60.61I	*(2012)*	58.39I	*(2017)*
Total water withdrawal *(10^9 m3/yr)*	560.6I	*(2002)*	531.7I	*(2007)*	469.1I	*(2012)*	444.3I	*(2017)*

Figure 1: Water Withdrawal Data by Sector 1998 - 2017[3]

Obsolete data and the failure to implement accurate methods to measure water resource availability are issues the USAF and DOD must address to ensure water security for the future.

1.3 Research Objective

The DOD reported in January 2019 that military installations were at risk of having insufficient water resources to meet their mission needs[1]. The 2017 *Annual Energy Management and Resilience Report* published by the DOD's Office of the Assistant Secretary of Defense for Energy, Installations, and Environment reported yearly reductions in DOD potable water consumption (Figure 2) while maintaining that military branches will continue to rely on water to carry out their missions[1,4].

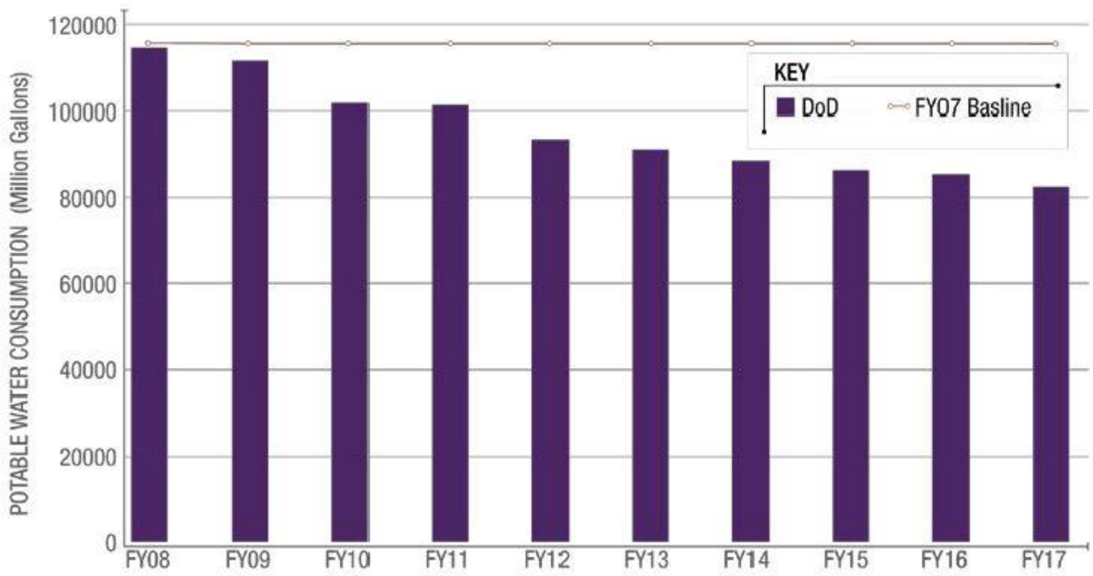

Figure 2: DOD Potable Water Consumption FY 2008 - FY 2017[4]

This research provides narrative on selected water scarcity indicators, which first were developed in the late 1980s when assessing water scarcity was recognized as a global issue[5]. Indicators assess water availability under given conditions and explanation is provided why particular ones were selected as the best choices to gauge water resources at the included USAF installations. Results from selected indicators are combined with local regional water use data to generate an index value as a measure of water scarcity particular to a location. Additionally, installation development plans (IDP) from each location were reviewed for content that refer to water scarcity. Appendix A.1 provides a summary of collected IDP data that are compared with the developed index results to assess for correlation.

1.4 Research Questions

The objectives from the previous section are the initiatives this research proposes to address. A study published in 2020 stood on the idea that water will be the primary medium that climate change impacts will be felt, and therefore it is imperative that enhanced water security be an intricate part of climate change response[6]. While many factors contributed to water security, the solution must provide framework and motivation that advocates for a method to measure water security across USAF locations. The following research focuses primarily on collecting available resources reflective of water scarcity conditions with the purpose of determining how each may contribute to a greater overall understanding of water scarcity. Additionally, cyber-attacks on the water supply sector are a growing concern. A 2019 publication by the American Water Works Association cited that the Director of National Intelligence, the Federal Bureau of Investigation, and the Department of Homeland Security concur that cyber risk is a top threat to critical water infrastructure in the United States[7,8]. For this reason, cyber risks to entities that supply water to USAF installations must be considered in the overall discussion for water security. Primary questions this research aims to address are:

1. Does a lack of water security leave USAF installations at risk from a perspective of mission readiness?
2. Will lack of water security subject USAF installations to vulnerability in the future?
3. What can enhance the USAF's determining factors for water security from a long-term planning perspective?

1.5 Motivation

Recent publications authored by representatives of the USAF and the DOD recognize that climatic impacts demand greater consideration in future water security planning, and past methods that address at-risk installations may not have been leading practices[1,9]. The Government Accountability Office (GAO) specifically identified that no effort was made to identify future water availability nor was an account for all ground and surface water sources included[1]. Decisions to ensure improved research and corrective steps must be implemented or the status quo of data inadequate to deliver water security answers will continue to affect military installations. The United States Army found that using utility privatization to upgrade utility infrastructure reduces risk and liability by transferring asset responsibility to local utilities, thus providing them a water resilience benefit[4]. While these contracts offer tangible advantages, the relinquished control of signing over water responsibilities may indicate that installations could be removing themselves from the ability to shape water resource strategy and maintain internal cyber risk protection. Despite the motivation from these benefits and the potential of decreased burdens on USAF installation municipal technicians, privatization agreements could expose the USAF and the DOD to risks that could threaten future mission assurance.

1.6 Preview

Chapter 1 presents how water security across the DOD and USAF is an under-valued national security component with insufficient data and practices to safeguard its protection. Content that motivates a response to the research objectives and water security considerations for the USAF is presented here. Chapter 2 is a literature review

that investigates different water security metrics, indicators, and indexes. Descriptions of each provide the value potential to developing quantifiable water security understanding at USAF installations for use in research and planning. Also discussed are government reports on past methods and future steps being considered to address growing water concerns, including failure to adopt industry leading water assessment practices and assessing risk[1,9]. Chapter 3 introduces the selection and development of inputs used to establish the index. Methods outline the paring down of large datasets into a scale that is both usable and applicable. Steps taken to extract IDP water resource information for use in conjunction with the developed water scarcity index are detailed. Individual water scarcity assessments assembled with selected IDP data is presented and examined in chapter 4. Chapter 4 also provides discussion to explain the relevance of the results and refers to visual aids to convey the significance of findings. Maps, tables, and plots display values in this chapter and in the appendix section to provide lasting interpretation for readers. Chapter 5 summarizes content of the research and offers motivation and recommendations for future water security. Additional consideration on the possibility of domestic terrorism threatening water security is also included.

II. Literature Review

2.1 Chapter Overview

The purpose of this chapter is to provide background of water scarcity indexes and the inputs that fit their primary applications. Each index bridges a gap in water resources research and meets a specific purpose of quantifying water availability. Not all indexes below are applicable to assessing water scarcity at USAF installations across the contiguous 48 states. Those not selected for development of the water scarcity index in this effort can still offer significance to the foundation of research.

2.2 Considerations for Research

Locations known to be at risk of a water uncertain future would be prudent to act in securing access to supplemental resources. Commonalities in regions of similar climate and geographic location exist, but water source-type, varying demand needs and influences of climate change are factors that introduce uncertainty to water awareness. These elements must be considered when selecting a scarcity indicator to represent location-specific water concerns. In planning to address water security challenges in the future, a precursor for execution is to first establish a mechanism to measure it[6]. This process is accomplished by selecting indicators that frame a location's water supply and demand conditions, that through calculation will translate into a usable water index score.

2.3 Water Scarcity Indicators, Indexes, Ratios and Assessments

Selecting an index or indicator best suited to capture a locations' water resource conditions should begin with understanding the differences between the two terms. First, an indicator is a grouping of variables, based on knowledge and scientific judgement, that

communicate information about the water resources system. Subsequently, an index represents an aggregation of indicators which are weighted to meet desired social preferences[10]. Figure 3 below lays out how research data can be pared to form indicators, and a collection of select indicators to form an index to shape policy for water resource planning[10].

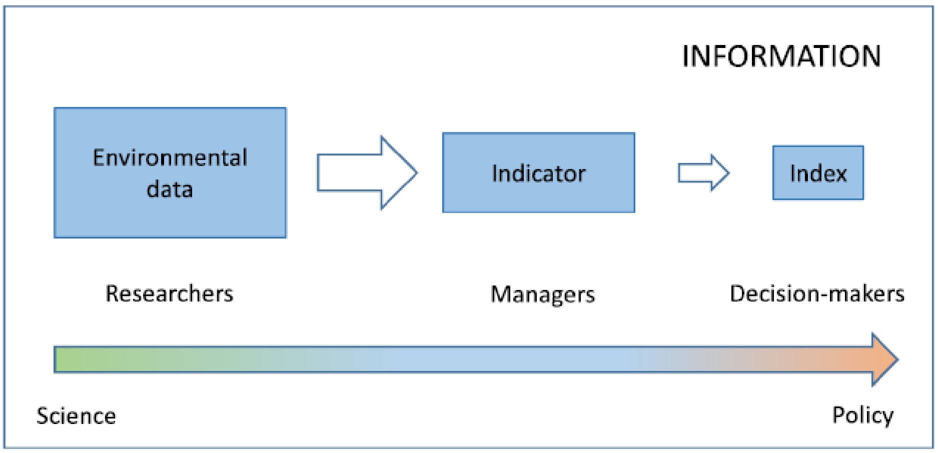

Figure 3: Aggregation of information in water resource planning and management[10]

Development of an accurate water security index is a tool that decision-makers can use to responsibly and effectively delegate resources to address the water needs of their region.

There are a variety of indexes comprised of weighted indicators developed to capture the availability of water, classified by characteristics of water scarcity[5]. The main purpose of an index is to quantify what cannot be measured directly, and to also measure the changes. A suitable index must be an assembly of properly selected components, built on reliable and accurate sources of data, of a sound formula, and subjected to a determined time frame for basing calculations[11].

The following is a collection of tools used by the water research community aimed to quantify the water conditions throughout various parts of the world. Each

subsection includes descriptive information about the type, including its applicability to water resource planning for the USAF. Additional reasoning is provided for the decision to include the three indicators selected as components for the index in this research.

2.3.1 Falkenmark Indicator

The Falkenmark indicator is recognized in the water scarcity field as a cornerstone for framing many other water scarcity indicators and indexes. First published in 1989, the Falkenmark indicator sought to quantify the water critical perils that Africa's semi-arid countries were facing, with particular regard to quality of life and food security[12]. In it, water scarcity is assessed by measuring per capita water availability from surface and subsurface resources (Eq. 1). Obtaining an accurate result requires the number of people living in a sector and the volume of water available for use within that domain[5]. Calculating yearly water availability per capita generates a number where trends predicting water shortages are easily observed over a selected time frame.

$$\textit{Falkenmark Indicator} = \frac{\textit{Water Availability}\ (m^3/\textit{Person})}{\textit{Year}}$$

Eq. 1

The Falkenmark indicator could provide useful contribution for an index to highlight water stress levels of a location. The validity of the assessment is subject to the availability of the data input into Eq. 1. The Falkenmark indicator overlooks temporal characteristics and the primary drivers of demand related to economic growth, lifestyle, and technological developments[5,13]. Because of such omissions, the Falkenmark indicator is not a universal fit to capture variability of water scarcity demands at USAF locations.

2.3.2 Criticality Ratio / Water Use to Availability Ratio

Criticality ratio measures water stress by calculating the ratio of water use to availability and is another widely recognized method to gauge water scarcity. This ratio measures the amount of water used and relates it to the available renewable water resources[5,14]. Water use refers to both water consumption and water withdrawals, which differ greatly in volume, so it is important to understand each. The water consumption measure is volume lost through evaporation to the atmosphere from rivers, lakes, and other groundwater sources[5]. Consumption is a fraction of withdrawal, and therefore the amounts minimally impact water scarcity[15]. Water withdrawal refers to the volume of water intentionally removed from rivers, lakes, and other groundwater sources for use[5]. Worth including in determining withdrawal amounts is that some removed portion is returned to the source after use and treatment. This return of measured flow that can be metered at treatment facility effluent points may suggest a fairer assessment of the stress on a water resource as the overall take is reduced noticeably by this replenishment.

When the water use to availability ratio, an alternate name and more descriptive verbiage of criticality ratio, exceeds 40 percent withdrawal, this rate is considered high water stress[14]. Criticality ratio is a practical assessment tool for determining water scarcity. Commercial and public use water withdrawal, and treated return amounts are metered data that is stored and available for analysis. Flow volumes from water sources like streams and rivers are also monitored and can provide the water availability portion of the analysis. As previously mentioned, including the return flow calculation makes this assessment a more accurate measure when looking at the entire water scarcity picture. The criticality ratio is a direct assessment on the collective state of a region’s water

condition. Assuming that data input for the criticality ratio is accurate and encompassing, this assessment would be a strong choice to determine water conditions at a desired location. Limiting factors for using in this research is the ability to collect data for each region's available water sources, but it could be a useful assessment for USAF application if this could be accomplished.

2.3.3 Water Poverty Index

The water poverty index (WPI) was designed to address water issues in less developed regions. Areas facing poor or non-existent water utility infrastructure, coupled with the burden of no resources to improve their circumstances are parameters the WPI was designed for. The five indicators in the WPI make-up are: water availability; access to water for human use; effectiveness of people's ability to manage water; water use for different purposes; environmental integrity related to water and of ecosystem goods and services from aquatic habitats in the area[16].

The WPI formula generates a weighted average of the five components, with the final index being on the order of 0 to 100. High values indicate higher levels of water poverty[5,17]. The WPI is encompassing by including multiple aspects that could affect water access at a select location. While the broad considerations of the index could be viewed as a strength, accurately generating a value could pose challenging due to the five-component data collection requirement. Couple this with the WPI being designed primarily to indicate water conditions of regions faced with limited water resources and poor adaptive capacity suggest this would not be suitable to convey future water needs of current USAF installations. While not a fit for this research that focuses on established

regions, the WPI could provide a valuable outlook to the USAF and the DoD if occupation of an undeveloped austere location were directed.

2.3.4 Green-Blue Water Scarcity Indicator

Other models boasting more sophisticated methods have been created in the 21st century with emphasis on the use of spatial analytical tools[5]. The green-blue water scarcity indicator accounts for green water which refers to soil moisture in the unsaturated zone recharged by precipitation, and blue water which is quantified as the total run-off of renewable freshwater on the earth's surface or ground water[5]. Incorporation of both water types is rooted in the indicators' primary purpose as a resource for agricultural production. Because of the emphasis on green water which is largely not considered a source for direct human consumption, this indicator would have limited application to directly address water scarcity at USAF locations. However, installations located in regions of moderate to heavy agricultural landscape could focus on the components and results of this indicator to assess what demands were being placed on each resource type. Such information could help shape where to focus effort to tap into water resources that have not yet been subjected to development.

2.3.5 Water Footprint-Based Water Scarcity Assessment

Water footprint-based water scarcity assessment measures the amount of water used to produce the goods and services humans use[18]. This assessment incorporates return flows back to resources that some other models fail to account for. Three components are considered to measure water use and availability: consumptive use of ground and surface water flows-i.e. the blue water footprint; the flows needed to sustain

critical ecological functions are subtracted from water availability; water use and availability are measured on a monthly rather than annual basis to account for seasonal water scarcity[5]. The result from this indicator provides where and when water level use is likely to cause shortages and ecological harm within identified river basins. Risks to ecological health and ecosystem services are recognized when the 20 percent removal level is surpassed. The environmental flow requirements (EFR) counted as the remaining 80 percent is a broad approach that fails to consider specific river flow amounts or regional withdrawal needs as all river basins were considered in this number[5,19]. Many studies found that appropriate levels of EFR vary across the river regimes considerably, which further refutes the EFR value of 80[20]. The complexity of required components for this indicator may post greater challenges due the greater burden of collecting more data points. However, the analysis is comprehensive and the component of measuring on a monthly scale would provide the USAF a detailed foundation of results to use in planning decisions. This assessment would be a strong choice for the USAF if input data could be gathered to complete the calculations.

2.3.6 Cumulative Abstraction to Demand Ratio

Water availability is seasonally variable across many regions, with resources exceeding demand in some months and falling short in others[5]. The cumulative abstraction to demand (CAD) ratio is an indicator that applies global hydrological model results that simulate river flow volumes and water removal at a daily time step. The calculated values are expressed as a ratio of cumulative daily water abstraction from rivers to the cumulated daily potential water demand made up of agricultural, industrial,

and domestic uses for a selected year[5,21]. Due to the input components of the CAD, it would be most applicable in regions where a vast majority of water withdrawals come from surface water. Because the results reflect seasonal variations of water scarcity brought on by drought conditions, selecting CAD as an assessment would exemplify the influences of climate variation. Using this ratio as an indicator would provide a strong collection of water scarcity information in surface flow dominant regions if the high quantity of data computations could be overcome[5]. This would be an appropriate method for the USAF to assess water scarcity conditions if a significant portion of an areas' water supply were extracted from surface water resources.

2.3.7 Blue Water Stress Indicator

Blue water refers to liquid water in rivers, lakes, wetlands and aquifers [22]. A panel of heads of state from around the world in September of 2015 adopted the *2030 Agenda for Sustainable Development* that consisted of 17 Sustainable Development Goals (SDGs)[23]. One of the SDG indicators selected to monitor water scarcity was the blue water stress indicator. The blue water stress indicator is practically identical to the water footprint-based water scarcity assessment detailed above, with both measuring for ground and surface water flows[5]. Blue water scarcity is a collective ratio of total freshwater withdrawn by all sectors to the total water availability in a designated region, the equation for which is shown below (Eq. 2)[23]. The water stress (WS) percentage is achieved by dividing the total freshwater withdrawn (WW) by the total renewable water resources (TRWR), less the environmental flow requirements (EFR).

$$\boldsymbol{WS}(\%) = \frac{\boldsymbol{WW}}{\boldsymbol{TRWR - EFR}} \times \mathbf{100}$$

Eq. 2

The subtraction of the environmental flow rate (EFR) from the total renewable freshwater resources (TRWR) accounts for the gross water abstractions that are returned, accounting for the consumed portion[23]. Approximately 10 percent of the domestic take of gross water abstraction is lost to consumptive uses[24]. The direct connection to a region's water availability and use characterized by the blue water stress indicator represents an ideal tool for USAF water assessment. The practical and direct approach combined with an available data source were reasons the blue water stress indicator was included for index development in this research.

2.3.8 Baseline Water Stress Indicator

Baseline water stress measures the total annual withdrawals of municipal, industrial and agricultural consumers from the total available blue water resources in a region[25–28]. Higher values indicate more competition among users, so demand increase from any of the three sectors would drive an escalation. The calculation for this indicator (BWS) divides water withdrawals (WD) by mean available blue water (BWA-avg), shown here in Eq. 3.

$$\boldsymbol{BWS = \frac{WD}{BWA - avg}}$$

Eq. 3

The output is a direct quantifier of the risk to a region due to the collective strain expressed on its blue water. While inputs for the calculation are shared with other measurement options referenced in this section, this method is another that offers

relevance and useability to provide an assessment of water conditions at USAF installations. The baseline water stress indicator was selected at a component of the index developed to add robustness by emphasizing blue water as a key indicator of water scarcity.

2.3.9 Groundwater Stress Indicator

Groundwater stress (GWS) measures the ratio of groundwater withdrawal relative to its recharge rate over a given aquifer[29]. This indicator also called the groundwater footprint (GF) is a water balance between aquifer inflows and outflows show below in Eq. 4. The area-averaged annual abstraction of groundwater is denoted by C, the recharge rate by R, and the groundwater contribution to environmental streamflow by E. Any areal extent where C, R and E can be defined is denoted as A, measured in units of length squared.

$$\boldsymbol{GF = A[\frac{C}{R - E}]}$$

Eq. 4

An aquifer is still considered part of the blue water footprint as they contain or transmit groundwater accessible to withdrawal. Including this measure of another primary water source in this research index facilitates representation of water conditions at locations with low or no available surface water resources. Limited availability of surface water resources does not necessarily equate to an area being water scarce, so by including a GWS indicator this potential gap to complete a water scarcity assessment is filled. For GWS, regional values that have a raw score above one suggests that excess consumption could be detrimental to sustainable groundwater availability, namely where

the ecosystem is groundwater-dependent[30]. This indicator would be useful to the USAF to gather water scarcity data from regions with multiple water resources.

2.3.10 Summary Table

Table 1 below provides a summary of the above water indicators by name, a brief description and the source(s).

Table 1. Table of Water Scarcity Indicators

Water Scarcity Measurement	Description	Source
Falkenmark Indicator	water availability per person per year	5,12
Criticality Ratio	ratio of water use to availability	5
Water Poverty Index	five component formula designed for use in less developed regions	5
Green-Blue Water Scarcity Indicator	measures green and blue water for use in agricultural application	5
Water Footprint-Based Water Scarcity Assessment	measured at a monthly rate, incorporates return flows and indicates shortages	5,18
Cumulative Abstraction to Demand Ratio	ratio of daily abstraction from rivers to demands of agricultural, industrial and domestic uses	5
Bluewater Stress Indicator	ratio of total freshwater withdrawn to a region's total water availability	23
Baseline Water Stress Indicator	measure of collective withdrawal from the total available blue water resources	25–29
Groundwater Stress Indicator	groundwater footprint is regional measure of groundwater extracted to the recharge rate	25,29

2.4 Installation Development Plan Review

Installation development plans (IDP) are USAF reports that provide a comprehensive look into a bases' strategic vision. Aiming to help decision makers prepare for the future are sections labeled: strategic vision alignment, installation setting, planning constraints, installation capacity opportunities, sustainability development indicators, future development planning and plan implementation. Separate sustainability development indicators focusing on water quantity, quality and intensity provide conditions specific to potable water at each USAF installation, including the characteristics of unique cases. The climatic vulnerability section provides a table of potential threats from the natural environment, each with a current assigned value to reflect the potential magnitude at the installation. The fundamental water conditions in conjunction with the climatic vulnerability measures provide information that reveal where stronger water planning actions may be needed. These records aide in closing the gap that must be filled to achieve water security at vulnerable USAF locations.

2.5 Summary

Content from the 2020 publication Air Force Civil Engineer Severe Weather/Climate Hazard Screening and Risk Assessment Playbook and the 2019 United States Government Accountability Office report to the United States Senate on water scarcity strongly indicate that insufficient planning and action measures have been in place to address for potential water insecurity at USAF locations. The GAO found that leading industry practices to identify and analyze water scarcity to shape a reliable assessment of water availability were not part of the roadmap to address realized

concerns[1]. By also considering the current information being supplied in the IDPs, this research intends to highlight any shortfalls that can be fulfilled by adopting better methods to assess water supply risks. The nexus of leading scientific methods with local base affiliates will empower those tasked with directing water management responsibility to be leaders for promoting measurable change.

III. Methodology

3.1 Chapter Overview

The following introduces the steps used to select USAF installation locations, how metrics and indicators were chosen to represent water scarcity conditions and the methods followed to generate results. ArcMap™ GIS software was the designated platform to project parameters and join selected indicators for data sets and visuals. Tables in the appendix section list the installations selected for analysis and a map (Figure 4) of their locations is provided below in this section. The progression of searching the selected base IDPs to collect information relevant to the current understanding of water security is separately discussed. Explanation of the ordered ranking of bases by each indicator is provided. Lastly, steps of how the final index score was created by averaging the rank value of each indicator is summarized.

3.2 Data Collection

3.2.1 Selection of USAF Installations

Research findings of publications in the field of water research in the United States revealed that water scarcity data and general research for Hawaii and Alaska was more limited than for the lower 48 states. Gathering data for the states separated from the contiguous 48 would have required a disproportionate amount of effort. For these reasons, this research did not consider USAF installations or water scarcity in Hawaii or Alaska. Of the remaining 48 states chosen to study, 34 USAF installations were selected from all major commands (MAJCOMS) with the primary objectives being diversified climate and geographic location. Installations with moderate proximity to another that

may not have offered a diverse climatic and geographic characteristic were excluded from analysis. Figure 4 shows a map for the 34 chosen installations, sorted and projected from a United States Military installation shapefile[31].

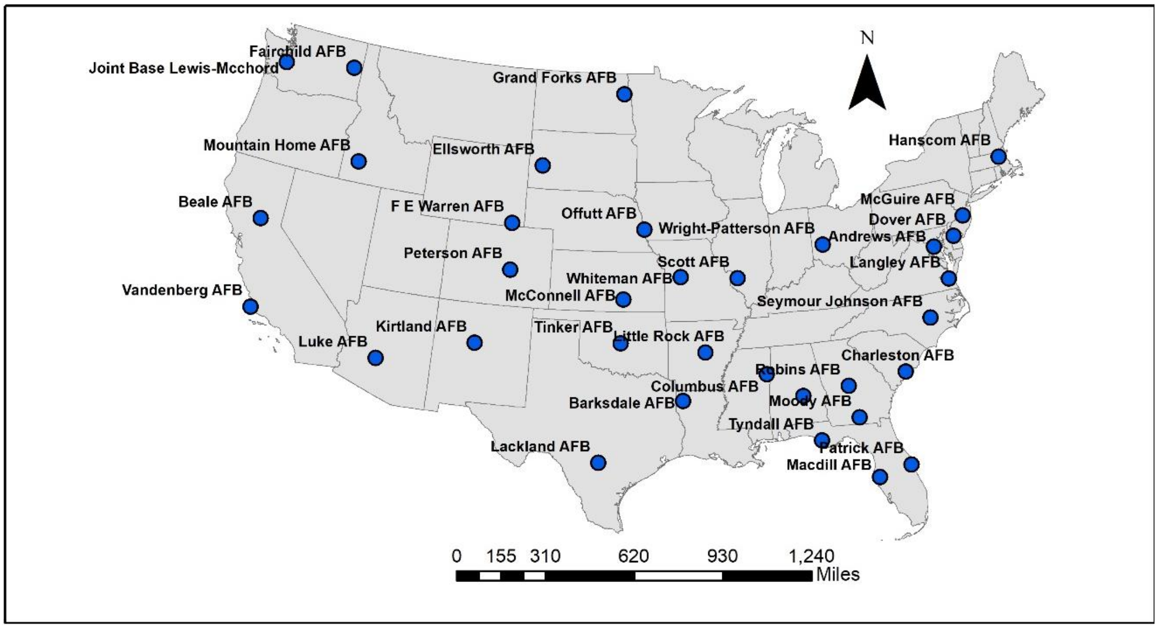

Figure 4: USAF Installations Selected for Analysis Across MAJCOMS

3.2.2 Selection of Indicators

The four components chosen to generate the index represent an approach to installation water scarcity. Each indicator denotes a useful contribution to capture a different understanding of a water availability characteristic. The blue water scarcity component represents the ratio of blue water footprint in each river basin to the blue water available[18,32]. This component accounted directly for scarcity of available water in surface and ground water sources, and is important as blue water is the primary term for what is available for human use[33]. Baseline water stress (BWS) measures the total annual water withdrawals, expressed as a percentage of the total annual available blue water[26–28].

Including BWS accounts for withdrawal strain that is put on a location's blue water resources. Groundwater stress measures the ratio of groundwater withdrawal relative to recharge rate. Selecting GWS represents the demand placed on a region's sub-surface water resources. The generated indicator of overall water consumption per capita per year represents the fourth component to round out a location's water scarcity condition. Combining these different measures of available water resources accounts for potential variability at each location.

The value ranges of each component vary to different degrees, shown by the standard deviations of each in Appendix A.2. Each index component was first ranked from 1 to 34 with the highest measure of water stress or consumption being assigned the number one ranking. Any equal values were ranked the same and the next increase assigned the value in the progressive numeric sequence. These rankings from each of the four indicators were combined by averaging at shared base locations. This average was ranked one final time to order the selected installations from 1 to 34, one equating to the most water stressed installation.

The intersection of the base locations projected onto the HUC8 basins with associated GWS data in some cases provided no output as a value in the database was not available. For these occurrences, a GWS score from a basin adjacent to one containing the USAF installation was substituted. Selection for a substitute GWS value from an adjacent basin was predicated on that basin possessing the most similarity in other water scarcity measures common to both.

3.2.3 Developing the Water Use Per Capita Component

The United States census database contains 2010 population shapefiles used to develop surface water availability per capita values[34]. ArcMap™ feature class tools removed demographic-specific quantifications from the dataset, as only total population quantities were considered. Hydrologic unit code data at the 8-digit basin level (HUC8) supplied the water use portion to adjoin with the population and establish the water availability per capita indicator[35]. The regional water use data in acre feet per year (AFY) was converted to cubic meters per year (m^3/yr). Use values from regions within each states' boundaries were summed to calculate the total water consumed by the total state population. A map projecting state-scaled water use per capita pushed the development of a more localized resource availability projection. The decision to create a water use per capita value was made in part as a measure of similarity to the Falkenmark indicator. The difference is that a Falkenmark result provides water availability and here the result is a measure of water consumption.

3.3 Data Synthesis

Shapefiles of the three existing indicators were projected onto a map of the contiguous 48 states. ArcMap's™ geospatial intersect tool extracted the desired value from each region where a USAF installation is located. Bases were ranked in each category by the extracted score from 1 to 34 in descending order of severity. Likewise, the water use per capita component was ordered with the most severe values assigned the lowest numeric ranking. Any ties in rankings were assigned the same number, and the next ranking level above a tie resumed the normal chronological progression. Production

of a final value came by averaging the base rank scores of the four contributing indicators. Scores were sorted by raw value to develop order, but then exchanged for the more cerebral chronological rank. This was adopted to prevent raw-value scores at uneven scales from dominating the result. The value of the final analysis displays an index of bases ranked from 1 to 34, with one representing the most water scarce.

3.4 Data Visualization

3.4.1 State-scale Water Use per Capita

The results of water use per capita at the state level were projected onto a heat map (Figure 5) of the lower 48 states. The visual outputs from this extensive-scale projection seemed broad to accurately reflect water conditions at designated region occupied by a USAF installation. Recognizing the need for more spatially accurate representation drove development of water use per capita at the HUC8 basin level.

3.4.2 Basin-scale Water Use per Capita

Creating a more spatially appropriate projection began with overlaying population density with an 8-digit Hydrologic Unit Code (HUC8) for regional boundaries[35,36]. Every state's county area from the census tract shapefile was divided by 1,000,000 to convert square meters to square kilometers, and this result filled a new column in the data table. A column for population density was added and filled by dividing the population by the area of the corresponding census tract to output the number of people per square kilometer. Using the geoprocessing clip tool and the HUC 8 boundaries as the clip feature, segments of states with their assigned population density values were grouped by a shared HUC identifier, aptly named HUCID. The shapefile data table was transferred to

Microsoft Excel for further calculations. The areas from the basin clips of state segments were multiplied by their individual population densities to produce a population for each. These populations were summed by associated HUCID, and a new population for each HUC 8 basin was generated. Assigning population by HUC 8 basin permitted for intersecting blue water scarcity, baseline water stress and ground water stress indicators assigned to the same HUCID. Overlaying a shapefile of USAF installations selected for this study allowed pinpointing of the indicator results at each location[31].

3.4.3 Data Extraction from Installation Development Plans

Combining the analysis extracted from the IDPs with the generated water scarcity index results provides an opportunity to compare current water scarcity evaluation measures at USAF installations. Key word searches in each IDP document produced hits for the phrases ‘climate change’ and ‘water security’ with results provided in Appendix A.1. The section from each IDP relating to sustainability development indicators contained a narrative of values for: privatized water systems, mission expansion capabilities, assigned drought rating value, installation water availability during peak demand, water supply headroom during peak demand, water source type and climatic vulnerability ratings for other sustainability development indicators. Assembling these values into tables allows for comparative analysis with the generated water scarcity index and the measures currently being considered in installation water planning.

3.5 Methods Summary

The preceding steps show the processes taken to gather, sort, pare down and present the data. The culminated result of these efforts will be represented in the

following section in the forms of visually useful figures, tables and graphs. The results are analyzed and their contribution opportunity for shaping the water security domain is considered.

IV. Results and Discussion

4.1 Chapter Overview

The analysis below considers the relevance and ranking of the indicators chosen to highlight existing water scarcity conditions at the selected USAF installations. The importance of data presented at the correct spatial scale to meet needs specific to local population is relevant to the integrated study of water, as different disciplines favor different scales of analysis[37]. Maps shown in Figure 5 and Figure 6 and values in Appendix A.4 reveal the measurable differences in value of the two options considered. Indicator scores for each installation are averaged and an ordered final index serves as a platform to reveal how water scarcity can be used in planning. Installations whose final index rank indicate a water scarce condition are examined in conjunction with findings collected from the IDPs. Adopting a plan to ensure mission readiness for the USAF from a water security perspective must be predicated on an effective measure to identify water scarce locations. Only then can steps be taken to mitigate against the detrimental sources. The numerous uses that USAF installations rely on water resources for are included to bring recognition to the importance of long-term water security to national defense.

Identifying external factors and influences beyond an index to reveal water security will be vital moving forward. Water resource sustainability development indicators and other reported data captured from IDPs were found to provide limited contribution to assessing water security. While not a primary objective of this research, climate change is a dynamic factor that must be considered when ascertaining future water security plans. Finally, the lack of in-place water security measures aimed at

protecting water resources from cyber threats is considered as an area for future action as the USAF may be failing to designate proper attention to this growing risk. The DOD's 2017 Annual Energy Management and Resilience Report stated that cyber security and mission assurance policy are applicable in reducing costs of operating and maintaining infrastructure, summarizing that disruptions caused by system deficiencies or adversarial attacks are usually costly impacts[38]. Failure to address water security now has the potential for high fiscal and operational impacts in the future.

4.2 Measuring Water Scarcity Key to Plan Development

In its 2019 report on water scarcity, the GAO confirmed that the DOD did not have assurance regarding the data being used to inform which installations were at risk for water scarcity. Six assessments on installations vulnerable to water scarcity evaluated by the Office of the Secretary of Defense (OSD) and military departments were found to have very different results which raised questions to the GAO about what sources of information were being trusted to make their determinations[1]. The report regarding the integration of uncertainty into United States water resource planning referenced in the publication's introduction section suggests that data limitations are a persistent problem[1]. The assurance of correct data is key to executing a calculated and steady response to meet growing water needs. In the long-term this will promote an economically feasible advantage versus reactive measures to address already developed problems.

Developing a plan to increase water security requires first establishing a method to measure it[6]. Understanding the inputs and implementing the combination of selected indicators to create a decipherable output are keys to realizing progress from an initial

baseline. A useful output will be formulated by environmental data entered into an appropriate indicator that decision-makers will use to develop an index for their water scarcity policy[10]. Some variability both on the initial collection and subsequent measurements should be expected as input data carries inherit uncertainty.

The analysis summarized in Appendix A.1 highlight the overall lack of measurables being reported at the base level. Information useful to the direct measure of water scarcity was not revealed in current IDPs. Only IDPs from Tyndall AFB and Joint Base McGuire-Dix-Lakehurst of the 34 reviewed mentioned water security, and in both cases the reference was for bolstering infrastructure rather than confronting the potential for water shortages. This is one example of an indication from the IDPs that allude how water security considerations have been undervalued at the base level.

The GAO water scarcity report identified five leading practices aimed at identifying and analyzing water scarcity risks. These five were selected from the Department of Energy and the United States Environmental Protection Agency list of 14 best management practices and principles[1,39]. The five leading practices are:

1. identify current water availability
2. identify future water availability
3. take into account all sources of water
4. precisely identify locations (of water)
5. comprehensively include all locations (of water)

The current reporting from IDPs focuses primarily on base demands and availability as calculated by headroom. Broader scope understanding of current and future water availability for the area is not considered. To aide in the measure of water scarcity, the

water quality and quantity sections within the IDPs should align more with the focus the GAO recommends for the DOD to implement.

4.2.1 State-scale Water Scarcity

The first water scarcity map developed in Figure 5 represents values of water use per capita at the state level. The state of Nebraska along with four others fall into the category representing values of highest water consumption per capita. When considering the percentage of collected water used for crop irrigation in an agriculturally productive state versus for domestic purposes, the rating of this calculation is better understood[40]. Even so, as populations are not distributed evenly across states, getting to a spatial scale that serves the distribution appropriately is a prime reason for implementing a finer resolution. As with a clearer understanding of the influential factors contributing to states like Nebraska, greater understanding of water scarcity conditions can be attained to improve water scarcity forecasting at USAF installations. While these results provide value as a step to forming an understanding for the full picture of water scarcity, the level of detail presented to construct regionally appropriate action plans fails to meet these requirements. A more precise representation of water use data is introduced in the next section.

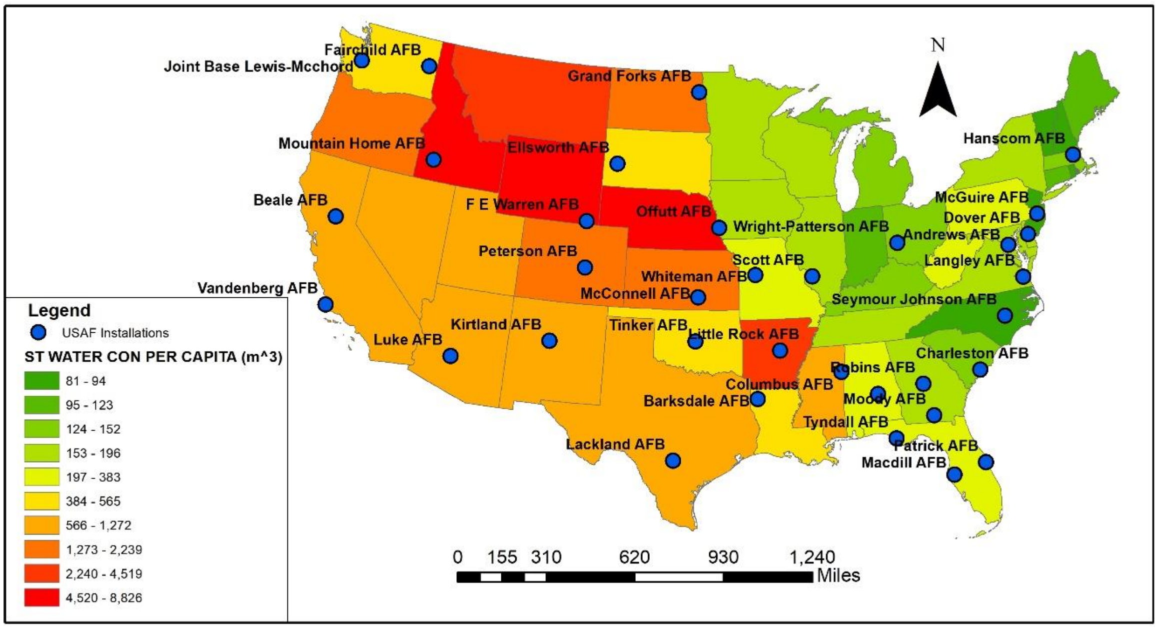

Figure 5: Contiguous State Water Consumption Per Capita Per Year

4.2.2 Using HUC 8 Basin Level Data for Localized Water Analysis

Many studies are carried out at a national or sub-national level. While useful, water security assessments at these levels can mask significant variations in water availability at the local scale[6,41]. Recognizing the limitations of a state-level water availability assessment led to developing a per capita usage at the HUC8 basin-level. The map in Figure 6 projects boundaries that are no longer state borders but HUC8 basins. In direction comparison to the state-scale in Figure 5, the visual outlook from Figure 6 suggests that water consumption per capita is best approached by local region rather than at the state level. A side-by-side comparison of calculated water consumption per capita results of both scales in Appendix A.4 shows that approximately 80 percent of the state-scale values at shared base locations are higher. This supports that developing a

regionally appropriate scale is an important tool to shape the water scarcity component for use in planning.

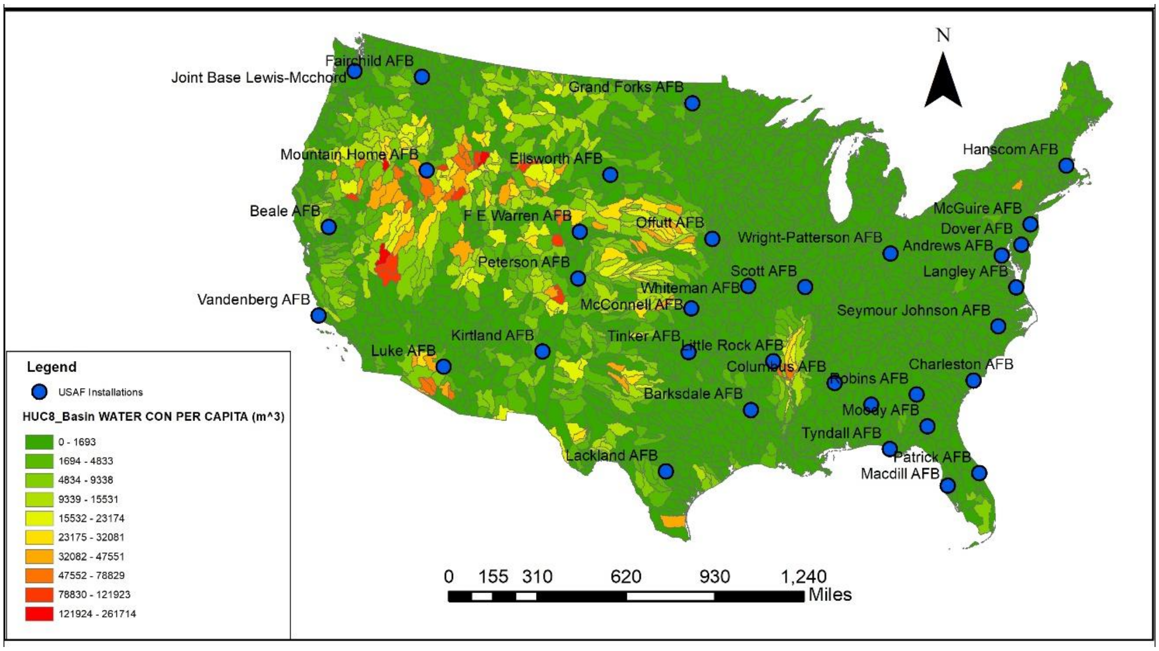

Figure 6: HUC 8 Basin Level Water Consumption Per Capita Per Year

4.3 Calculating the Water Scarcity Index

Water scarcity has become a major constraint to socio-economic development and a threat to livelihood in increasing parts of the world. Since the late 1980s, water scarcity research has attracted political and public attention. This research reviewed a variety of measurement tools developed to capture different characteristics of water scarcity. Population, water availability, and water use are the key elements of these indicators. A recent study on water scarcity assessments in the past, present, and future pointed out that most of the progress made in the last few decades has been on the quantification of water availability and use by applying spatially explicit models. Though, challenges remain on appropriately incorporating green water (soil moisture), water quality, environmental

flow requirements, globalization, and virtual water trade into water scarcity assessment. Meanwhile, inter- and intra-annual variability of water availability and use requires concerted efforts of hydrologists, economists, social scientists, and environmental scientists to develop integrated approaches to capture the multi-sided nature of water scarcity[5].

4.4 Calculated Result

The four components chosen to create the index are: blue water scarcity, baseline water stress, groundwater stress, and HUC8 basin water consumption per capita values. As covered previously in the background section, the blue water scarcity component represents a measure of total run-off of renewable freshwater on the surface of a given river basin[5]. The baseline water stress contribution focuses more on the availability of groundwater reserves from multiple contribution sources. The ground water stress indicator component highlights locations where the potential for drawing on groundwater resources may be limited due to unavailability. Finally, the basin scale water use per capita index component represents a value to compare availability at the selected installations.

In Appendix A.2 values for the basin scale water use per capita component at Wright-Patterson AFB and Columbus AFB appear to be outliers. The water use per capita values are unreasonably low as compared to the 32 other installations. While one could guess that errors in the original database are the root cause, the bigger take is that uncertainty exists in the data that is used in this analysis, and presumably others. The

element of uncertainty fuels the need to push for more consistent data and invest in research to quantify and understand water scarcity conditions at USAF installations.

4.5 Review of Recordings from Installation Development Plans

4.5.1 Installation Development Plan Data

Data from the IDPs was collected and summarized to provide analysis to better understand what current information could help shape the water scarcity picture. The table in Appendix A.1 shows the information gathered from the 34 USAF installations. A reference to climate change was only found in 7 of 34 IDPs. Results indicate an increase in the trend for privatization as nearly one third of the installations have or were actively pursuing to relinquish direct control of their water supply. The ability to accept more tenants or expand missions was confirmed for 28 of the 34 installations. This approval for expansion constituted having the water volume capacity to grow but failed to include analysis of water infrastructure age, which could contribute to the collective fiscal bottom line of the overall decision. Having adequate water supply positions installations with a competitive advantage for expansion opportunities, so this is an important component to their longevity. Of the 19 IDPs that included a drought score, 16 reported an index rating at the severe or extreme level of susceptibility. Headroom at peak demand is a measure of installation water availability, and most closely resembles one of the five leading practices identified in the GAO water scarcity report. Headroom at peak demand is a percentage measure of water supply available to an installation above their highest level of demand volume. Higher values represent greater reserve capacities. Though no threshold for a level of concern was given, 8 of 34 installations reported a headroom with

peak demand values of 25 percent or less. Yet only 4 of those 8 landed in the top 10 of the final ranking of most water scarce installations.

4.5.2 Comparative Analysis of Index and IDP data

To meet one of the objectives set in this research, a scatter plot was created between the final averages of the developed index and the IDP element that most closely aligned with a measure of water scarcity, headroom at peak demand. The result below in Figure 7 reveals essentially no relationship between a measure of water scarcity and the actual availability of water resources represented by headroom. This result suggests a need to adopt a method to accurately measure water scarcity, as apparent supply is not a reliable representation.

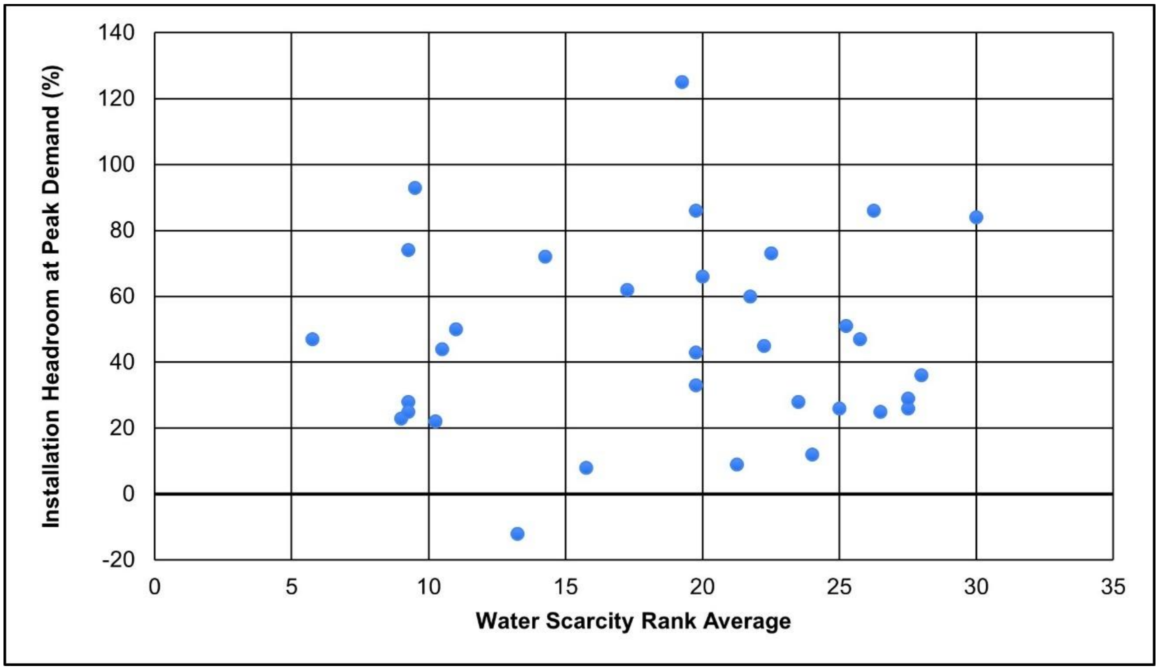

Figure 7: Water Scarcity Rank vs. Headroom at Peak Demand

4.6 Water Scarcity Index and OSD Assessment Results

Despite the findings from the GAO that the DOD did not have assurance in the practices used to confirm water scarcity, three OSD assessments considered eight USAF installations at risk for water scarcity[1]. These eight installations are shown in **Error! Reference source not found.** below.

Table 2: DOD Active-Duty USAF Installations Identified in the Office of the Secretary of Defense Assessments as Being at Risk of Water Scarcity[1]

USAF Installation	State Located
F.E. Warren Air Force Base	Wyoming
Joint Base Langley-Eustis	Virginia
Joint Base San Antonio	Texas
Luke Air Force Base	Arizona
McConnell Air Force Base	Kansas
Moody Air Force Base	Georgia
Mountain Home Air Force Base	Idaho
Vandenberg Air Force Base	California

Six of the installations identified by the OSD for being at risk for water scarcity also ranked in the top 10 of the index developed for this research identifying the most water scarce locations. **Error! Reference source not found.** below provides these top 10 installations and their index average. A complete ranking and index average of all 34 installations is shown in Appendix A.3. Though methods of assessment differ, commonalities of some installations being at risk for water scarcity from both sources may indicate a need for prompt mitigation action.

Table 3: Top 10 Indexed Water Scarce USAF Bases

Index Rank	USAF Base	Index Average
1	F E Warren AFB	3.75
2	Luke AFB	4.50
3	Ellsworth AFB	5.25
4	Mountain Home AFB	6.00
5	McConnell AFB	6.75
6	Peterson AFB	7.00
6	Vandenberg AFB	7.00
8	Lackland AFB	7.25
9	Kirtland AFB	7.50
10	Tinker AFB	8.00

4.7 Considerations for USAF Water Scarcity

4.7.1 Protecting Water Resources

Assessing water resources across the United States today requires consideration of multiple factors. Considering only a narrow framework would be detrimental as multiple stressors integrate to affect water security[37]. Installations presented with opportunities to adopt new missions must consider the security of a long-term water supply before agreeing to expansion. Competition from industrial, agricultural, and other domestic users will continue to put pressure on water resources despite downward trends in water usage[3]. Figure 8 below from the 2019 United States Government Accountability Office shows the areas that water is imperative for in the military. All category listings are no-fail status, so a loss of water supply would be detrimental to national defense.

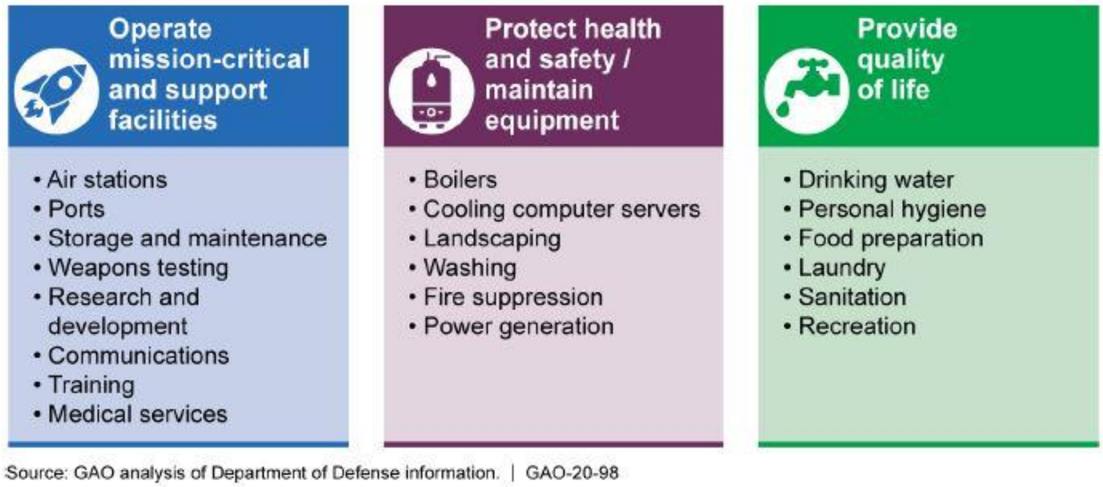

Figure 8: Categories and Examples of Installation Activities That Require Water to Conduct and Support Military Missions[1]

The USAF's decision at some installations to surrender responsibility for water supply to the hands of local municipal providers brings up concern for mission readiness. This may solve fiscal problems in the short-term, but a major downside from relinquished control is the inability to influence policy ensuring future water resources. Accounting for these factors poses a great challenge to those responsible for developing long-term water resource strategy to meet future projected demands. The DOD on behalf of the USAF must pursue action plans that consider the full breadth of factors when planning for a water supply capable of sustaining long-term needs.

4.7.2 The Impacts of Climate Change

The definition the DOD recognizes for climate change states, variations in average weather conditions that persist over multiple decades or longer that encompass increases and decreases in temperature, shifts in precipitation, and changing risk of certain types of severe weather events[9,42]. A report from 2012 regarding climate impacts

on national security suggest that energy decisions and defense infrastructure are among the sectors that are already threatened by climate change. The report concludes that over the next few years the risk of "major societal disruption from weather and climate-related extreme events can be expected to increase"[43]. Past records of data and models projecting future climate change impacts on water scarcity must be an integral part in determining water security planning.

4.8 Summary

The methods to develop an index at USAF installations was one approach to generating a measure of water scarcity. No evidence of correlation between the water scarcity index values and the IDP data was concluded in the comparison. Comparing the index with data collected from IDPs drive the fact that reported measures beyond what is currently being asked from installation water managers must be expanded.

Nearly every operation on USAF installations holds a common link of reliance on a viable water source. For reasons of maintaining mission readiness to ensure national defense, water security must be a top consideration moving forward. Failure to attain water security may leave some capabilities vulnerable to meeting their complete force capability if restricted by lack of available water resources. USAF leadership must first be informed of the significant impacts that failing to achieve water security would have. Then a push toward adopting proven scientific measures to design and execute methods to ensure water security will be accelerated. Doing so is key to maintaining readiness and strengthening capabilities to deter enemy threats on the global stage.

V. Conclusions

5.1 Chapter Overview

This section provides summary of the research findings. Recommendations for future research and action based on results from the previous section are provided as considerations to shape future water security planning. Understanding current water scarcity conditions is crucial to planning to meet the future water needs of the USAF. Enhanced data collection and addressing concerns over physical and cyber-attacks will also be vital components to a water secure future.

5.2 Significance of Research

As the GAO water scarcity report found, industry leading methods that correctly assess water scarcity levels are not currently practiced. The recommended five industry leading practices to assess water scarcity risk align with the research effort presented here. Adopting these recommendations begins with collecting and analyzing data that can properly identify current and future water availability. To effectively carry this out requires accounting for all sources of ground and surface water, then pinpointing their locations and being inclusive of all in the availability calculations. As the progress of this research discovered, applying measures at a fine-grain analysis will more accurately capture the spatial and other factor variations of water security[37]. The installations identified in this research as being the most water scarce were determined in part by indicators using data from the past. Water scarcity indicators applied in the future at desired USAF locations should be climate informed to account for changes in conditions

which will primarily influence variations in the availability of ground and surface water sources.

5.3 Limitations of Research

The water consumption per capita value used census data and water use data for only a single year. In order to more accurately capture water use trends it would be appropriate to assess water consumption on a yearly basis over time with a population estimate. There are unknown influences of water scarcity that are also not discussed in this research to include temperature values and precipitation amounts. Consideration of changing factors over time could be represented by a variability score to account for yearly fluctuations.

5.4 Recommendations for Future Research and Action

The depth of analysis provided in each IDP provides little beyond basic reporting of current potable water resources and a user designated drought score. The lack of correlation between an installation's calculated water scarcity index value and the measure of its reserve water resources data suggest that what is captured in current IDP reporting does not relate to the variability of the water scarcity metrics. While all data may be subjective to some degree from the individuals making final determinations, it would be prudent of the USAF to expand water and climate condition reporting in IDPs to enable a metric that better reveals water scarcity at installations. Possible categories that could be realistically filled in future IDPs to enhance the content to aid in understanding current and future water resources by base engineering personnel are:

- yearly water consumption by housing

- yearly water consumption from base operations
- yearly regional water consumption values
- yearly regional blue-water availability

Additional climate related categories could be recorded and tracked as well, but the aforementioned categories could be directly applied to a water scarcity indicator like the ones selected for the index in this research. Collected data not used directly for calculations would still be useful in assessing weather condition trends over time to aide in the water scarcity assessment. Procedures for collection methods and data input should be provided to ensure the highest levels of consistency and continuity to build a useful database and help shape the water security outlook the USAF needs in the future.

5.5 Alternate Planning Considerations

Enhanced security is a continual concern for the USAF. Prior to increasing privatization agreements at other installations, water providers should be able to demonstrate cyber security measures that adequately protect the water resources that their USAF customers depend on. Failure to require a high level of cyber protection will increase the vulnerability of water resources, inviting risks that could hamper USAF mission capabilities. Another potential source of risk could be the cyber security measures of utility companies that provide water outside of a privatization contract. The IDP review showed that 22 of 34 installations receive all or some of their water from a source other than a private well on the installation. In these situations, from the position of a traditional customer standpoint, the ability to influence cyber defense is minimal. The USAF would be prudent to have contingency plans in place should water supply

become compromised from an external attack. At minimum this would consist of a clean drinking water supply to meet the needs of an essential crew to maintain installation operations, or at the highest level a standby treatment facility that potable inflow can be diverted through to extract contaminates before they reach the distribution network. Preparing for all threats to water security at USAF locations is a process that cannot be compromised.

Appendix

APPENDIX A.

A.1 Data Summary of Installation Development Plans

Installation	Yr. of Rpt.	Climate Change	Water Security	Privatized Water System	Mission Expansion	Drought Rating/Score	Water avail. during Peak Dmd (Demand in M gpd)	Headroom at peak dmd (%)	Source
Wright Patterson	2014		X	X	X	D2	5.77	66	Well
Tyndall	2015		X	X	X	None	1.44	25	County Utility
Peterson	2014		X		X	D3	2.21	47	City Utility
Maxwell	2015				X	D1	2.47	84	City Utility
Macdill	2017	X	X	X	X	NA	3.3	8	City Utility
Luke	2014		X		X	D2	2.87	25	Well
Vandenberg	2019			X		D2	2.2	-12	County Utility +well to supplement
Tinker	2017			X		D2-D4	3.4	22	City Utility + Wells to supplement
Seymour Johnson	2018				X	NA	1.85	73	City Utility
Scott	2015			X	X	D2	3.07	29	City Utility
McConnell	2019	X			X	Med-High	1	50	City Utility
Moody	2015				X	None	1.4	9	Well
McGuire AFB	2015	X	X		X	None	1.4	28	Well
Whiteman AFB	2015				X	D2	1.6	36	Well
Robins AFB	2015	X			X	D4	1.8	47	Well
Patrick AFB	2017			X	X	NP	1.9	62	City Utility
Andrews AFB	2015	X		X	X	D1	0.9	43	City Utility
Barksdale AFB	2015				X	D1	1.2	26	City Utility
Beale AFB	2015	X			X	D4	4.3	125	Well
Charleston AFB	2017					NP	1.2	51	City Utility
Columbus AFB	2017					D1-D4	1.3	12	City Utility
Dover AFB	2016			X	X	None	2.1	33	Well

Ellsworth AFB	2017				X	None	2.8	23	City Utility
F E Warren AFB	2017				X	D3	2	93	City Utility + Well
Fairchild AFB	2014				X	None	6.1	45	Well
Grand Forks AFB	2017				X	None	1.4	26	City Utility
Hanscom AFB	2017				X	D2	0.3	86	City Utility
Joint Base Lewis-McChord									
Kirtland AFB	2016				X	D2	2.6	28	Well + City Utility
Lackland AFB	2018	X			X	NA	4	44	Well
Langley AFB	2017				X	None	2.2	60	City Utility
Little Rock AFB	2016			X	X	D3	0.5	86	City Utility
Mountain Home AFB	2017				X	D2	2.7	72	Well
Offutt AFB	2018					None	2.3	74	City Utility

*An IDP was unavailable for Joint Base Lewis-McChord

A.2 Values of Scarcity Indicators for Final Index

Base Rank	USAF Base Name	Blue WS Yearly Avg Value	Base Rank	USAF Base	Baseline Water Stress	Base Rank	USAF Base	Ground Water Stress Raw Value	Base Rank	USAF Base	Region Water Consumed/capita Value	Avg Rank
15	Andrews AFB	0.729543984	17	Andrews AFB	2.645669654	33	Andrews AFB	0.649	21	Andrews AFB	109.6045074	21.5
24	Barksdale AFB	0.232421994	34	Barksdale AFB	0	33	Barksdale AFB	0.649	26	Barksdale AFB	66.96430969	29.25
13	Beale AFB	1.221590042	22	Beale AFB	2.066361807	10	Beale AFB	6.377	3	Beale AFB	4238.758789	12
26	Charleston AFB	0.097453199	19	Charleston AFB	2.567337477	33	Charleston AFB	0.649	12	Charleston AFB	213.8909302	22.5
27	Columbus AFB	0.088000298	34	Columbus AFB	0	33	Columbus AFB	0.649	33	Columbus AFB	4.437716484	31.75
17	Dover AFB	0.54507	13	Dover AFB	3.041149697	33	Dover AFB	0.649	19	Dover AFB	118.9471207	20.5
8	Ellsworth AFB	2.64805007	1	Ellsworth AFB	5	2	Ellsworth AFB	9.04	10	Ellsworth AFB	228.7050018	5.25
6	F E Warren AFB	4.812389851	1	F E Warren AFB	5	2	F E Warren AFB	9.04	6	F E Warren AFB	509.2087097	3.75
30	Fairchild AFB	0.0504396	20	Fairchild AFB	2.411557571	33	Fairchild AFB	0.649	29	Fairchild AFB	50.30548477	28
20	Grand Forks AFB	0.331312001	26	Grand Forks AFB	1.183394259	33	Grand Forks AFB	0.649	4	Grand Forks AFB	2921.554199	20.75
21	Hanscom AFB	0.289324999	21	Hanscom AFB	2.380891814	33	Hanscom AFB	0.649	31	Hanscom AFB	40.78009033	26.5
22	Joint Base Lewis-M	0.280277014	34	Joint Base Lewis-M	0	34	Joint Base Lewis-M	0.134	24	Joint Base Lewis-Mcchord	91.51333618	28.5
4	Kirtland AFB	5.564939976	1	Kirtland AFB	5	11	Kirtland AFB	2.543	14	Kirtland AFB	197.564743	7.5
1	Lackland AFB	6.75676012	9	Lackland AFB	4.112264778	8	Lackland AFB	8.57	11	Lackland AFB	227.1968079	7.25
32	Langley AFB	0.016371	15	Langley AFB	2.97177735	33	Langley AFB	0.649	28	Langley AFB	53.23056793	27
14	Little Rock AFB	1.019649982	25	Little Rock AFB	1.212644296	33	Little Rock AFB	0.649	2	Little Rock AFB	5439.180176	18.5
1	Luke AFB	6.75676012	8	Luke AFB	4.660237549	1	Luke AFB	26.562	8	Luke AFB	461.1740112	4.5
7	Macdill AFB	3.009085	11	Macdill AFB	3.165851539	33	Macdill AFB	0.649	23	Macdill AFB	96.38340759	18.5
34	Maxwell AFB	0.0135446	34	Maxwell AFB	0	33	Maxwell AFB	0.649	16	Maxwell AFB	170.2934418	29.25
9	McConnell AFB	2.463570118	7	McConnell AFB	4.86617605	2	McConnell AFB	9.04	9	McConnell AFB	295.6471863	6.75
31	McGuire AFB	0.034072898	12	McGuire AFB	3.145631481	33	McGuire AFB	0.649	17	McGuire AFB	161.552063	23.25
25	Moody AFB	0.132514998	24	Moody AFB	1.26225553	33	Moody AFB	0.649	32	Moody AFB	28.8466568	28.5
10	Mountain Home AFI	1.799419999	1	Mountain Home AFI	5	12	Mountain Home AF	2.155	1	Mountain Home AFB	6332.382813	6
16	Offutt AFB	0.571920991	14	Offutt AFB	3.032913698	2	Offutt AFB	9.04	30	Offutt AFB	47.60227966	15.5
12	Patrick AFB	1.252740026	16	Patrick AFB	2.71995682	33	Patrick AFB	0.649	27	Patrick AFB	53.26809311	22
5	Peterson AFB	5.067560196	1	Peterson AFB	5	2	Peterson AFB	9.04	20	Peterson AFB	114.9708252	7
19	Robins AFB	0.369067013	23	Robins AFB	2.0140275	33	Robins AFB	0.649	7	Robins AFB	478.8753967	20.5
23	Scott AFB	0.234795004	34	Scott AFB	0	33	Scott AFB	0.649	15	Scott AFB	178.8892517	26.25
29	Seymour Johnson /	0.071055099	18	Seymour Johnson /	2.617754697	33	Seymour Johnson	0.649	25	Seymour Johnson AFB	87.5154953	26.25
11	Tinker AFB	1.429949999	6	Tinker AFB	4.897303906	2	Tinker AFB	9.04	13	Tinker AFB	207.3850098	8
33	Tyndall AFB	0.0144285	27	Tyndall AFB	0.072063575	33	Tyndall AFB	0.649	22	Tyndall AFB	102.7765503	28.75
3	Vandenberg AFB	6.756757	10	Vandenberg AFB	3.33763386	10	Vandenberg AFB	6.377	5	Vandenberg AFB	2219.532227	7
28	Whiteman AFB	0.0812563	34	Whiteman AFB	0	33	Whiteman AFB	0.649	18	Whiteman AFB	130.9430695	28.25
18	Wright-Patterson AI	0.544588029	28	Wright-Patterson AI	0.052951277	33	Wright-Patterson A	0.649	34	Wright-Patterson AFB	0.03942908	28.25
	Standard Deviation	2.204745901		Standard Deviation	1.801155985		Standard Deviation	5.345452832		Standard Deviation	1585.294132	

A.3 Final Base Index Rank Compiled from Scarcity Indicator Average

Index Rank	USAF Base	Index Average
1	F E Warren AFB	3.75
2	Luke AFB	4.50
3	Ellsworth AFB	5.25
4	Mountain Home AFB	6.00
5	McConnell AFB	6.75
6	Peterson AFB	7.00
6	Vandenberg AFB	7.00
8	Lackland AFB	7.25
9	Kirtland AFB	7.50
10	Tinker AFB	8.00
11	Beale AFB	12.00
12	Offutt AFB	15.50
13	Little Rock AFB	18.50
13	Macdill AFB	18.50
15	Dover AFB	20.50
15	Robins AFB	20.50
17	Grand Forks AFB	20.75
18	Andrews AFB	21.50
19	Patrick AFB	22.00
20	Charleston AFB	22.50
21	McGuire AFB	23.25
22	Scott AFB	26.25
22	Seymour Johnson AFB	26.25
24	Hanscom AFB	26.50
25	Langley AFB	27.00
26	Fairchild AFB	28.00
27	Whiteman AFB	28.25
27	Wright-Patterson AFB	28.25
29	Joint Base Lewis-Mcchord	28.50
29	Moody AFB	28.50
31	Tyndall AFB	28.75
32	Barksdale AFB	29.25
33	Maxwell AFB	29.25
34	Columbus AFB	31.75

A.4 Water Consumption Comparison Basin v. State

USAF Base	State-level Water Consumed/capita/yr (M^3)	HUC8-Basin Water Consumed/capita/yr (M^3)
Andrews AFB	182	110
Barksdale AFB	541	67
Beale AFB	958	4239
Charleston AFB	146	214
Columbus AFB	824	4
Dover AFB	181	119
Ellsworth AFB	565	229
F E Warren AFB	6544	509
Fairchild AFB	530	50
Grand Forks AFB	1646	2922
Hanscom AFB	149	41
Joint Base Lewis-Mcchord	530	92
Kirtland AFB	1217	198
Lackland AFB	859	227
Langley AFB	166	53
Little Rock AFB	4519	5439
Luke AFB	909	461
Macdill AFB	229	96
Maxwell AFB	258	170
McConnell AFB	1794	296
McGuire AFB	94	162
Moody AFB	181	29
Mountain Home AFB	8826	6332
Offutt AFB	6157	48
Patrick AFB	229	53
Peterson AFB	1389	115
Robins AFB	181	479
Scott AFB	196	179
Seymour Johnson AFB	91	88
Tinker AFB	565	207
Tyndall AFB	229	103
Vandenberg AFB	958	2220
Whiteman AFB	383	131
Wright-Patterson AFB	134	0

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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 074-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25-03-2021	Master's Thesis	September 2019 – March 2021

TITLE AND SUBTITLE

Water Security at United States Air Force Installations

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Pollock, John D., Captain, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/ENY)
2950 Hobson Way, Building 640
WPAFB OH 45433-8865

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENV-MS-21-M-258

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Intentionally left blank

10. SPONSOR/MONITOR'S ACRONYM(S)

Intentionally left blank

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Global water security is a growing concern that poses unique challenges that stem from geopolitical arrangement, regional location, and local climate conditions. United States national defense relies on an uninterrupted water supply to sustain operations to carry out its readiness mission. Accurate water security assessments are necessary for adapting to climate factors and to provide essential information to meet the changing needs of human water demand. This research presents how different water metrics are applied at various United States Air Force locations to measure water scarcity. Geographical Information Systems (GIS) software is used to conduct spatial correlation across the United States to identify ranges between the metrics.

Reported water condition data from 34 United States Air Force installation development plans was assessed for correlation with the selected water scarcity metrics, though no evidence suggesting a relationship between the developed water scarcity index and the installation development plan data was identified. The development of an index to accurately relay water scarcity conditions will improve the ability to overcome water planning and regional water management challenges and combat factors that contribute to water scarcity. Such measures are needed to ensure water security as United States water resources face challenges from climatic variation and the threat of cyber-attacks on water systems.

15. SUBJECT TERMS

Water security, water scarcity, index, indicator, installation development plan

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Dr. Christopher M. Chini, AFIT/ENV
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18