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Evaluation of Efficient Water Reuse Technologies for Sustainable Forward Operating Bases

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EVALUATION OF EFFICIENT WATER REUSE TECHNOLOGIES FOR SUSTAINABLE FORWARD OPERATING BASES

THESIS

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Abstract

A secure water source is essential to the resiliency and readiness of military installations and contingency operation locations, especially those located in the dry climates the Department of Defense operates in today. There are multiple issues of concern when identifying water sources, such as security, cleanliness, accessibility, and sustainability. Water resources pose a potential vulnerability to mission readiness in a remote, agile environment, such as a forward operating base (FOB). Having a secure water resource would help facilitate mission readiness in the contingency environment, offering the opportunity to be more resilient and cost-effective.

Current water treatment technologies present the possibility to perform direct water reuse to mitigate increased water needs. This research evaluates seven technologies for the prospect of water reuse in austere contingency locations, specifically evaluating greywater (wastewater from showers, sinks, washing machines, and dishwashers) reuse. While there is no perfect solution when using water reuse technologies, considering the cost, energy efficiency, and mobility of each technology helps determine which of the seven is the best fit for each situation. This research finds that the best overall solutions for a FOB of up to 500 troops are either the U.F. membrane systems or the AdvanTex AX Greywater systems. This ranking is based on the low cost, high energy efficiency, and high mobility of these systems. These systems would not provide the total demand for water for a FOB but mitigate the need for freshwater supply.

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EVALUATION OF EFFICIENT WATER REUSE TECHNOLOGIES FOR SUSTAINABLE FORWARD OPERATING BASES

1. Introduction

The United States military has had an enduring presence in the Middle East since 1990 (Bowman 2008). Most of these forces occupy Forward Operating Bases (FOBs) with missions lasting anywhere from 90 days and on. It is not uncommon for a mission to change or increase in length, requiring more permanent structures and resources. The current expectation is for these FOBs' potable water demand to be met with delivered bottled water or with treated source water. These options are costly and have unnecessary security risks. However, there are opportunities to reduce the demand for fresh potable water by recycling and reusing greywater. Greywater is the wastewater that comes from showers, sinks, washing machines, and dishwashers. Greywater contains fats, oils, detergents, etc., but unlike blackwater, it does not contain human waste.

Currently, there are three ways to supply US military FOBs with water: (1) ship or convoy in bottled water, (2) purify source water, and (3) use host nation water infrastructure. There are advantages and disadvantages to each of these alternatives. Shipping water is expensive, poses a danger and security risk, and adds an immense amount of stress to the logistics network. Source water might be difficult to find in the current operational theater as most Middle East climates are considered arid. The treatment of source water requires expensive equipment. Host nation infrastructure must be present for use, making it infeasible for more austere FOBs. Additionally, host nation water is not considered potable until treated by US forces. However, there is a fourth alternative for water supply in an austere environment: recycling or reusing wastewater.

This opportunity provides an alternative to water supply, or at the very least, lowering the initial water demand through supplemental treatment processes.

1.1 Water Demand on FOBs

FOBs, as defined by the US Department of Defense, are "airfields used to support tactical, CSAR [combat search and rescue] and reconnaissance operations without establishing full support facilities." (USAF 2012b). FOBs may be used for an extended duration. Support by a main operating base will be required to provide backup support for a forward operating base. FOBs are created with expeditionary standards, meaning that the initial purpose is to support mission durations of up to 90 days (USAF 2012b). While this may be the initial intent, it is not uncommon that these FOBs become a more enduring presence. Operation Joint Endeavor in Bosnia lasted a year but had the intent to be a short-term mission. As the peacekeeping mission's scope changed, it became necessary for increased time commitment (Lombardo 1998). The extension of a FOB's mission complicates resource supply operations as an initial temporary solution needs to become more permanent, creating a unique sustainment challenge.

Multiple tools and guidelines provide different standards on how much water is required for a FOB. The Combined Arms Support Command uses a tool that provides a factor of 128.7 lpcd (Anderson 2013). In comparison, the World Health Organization uses 50 lpcd as a fundamental human right (Anderson 2013). The United States Air Force (USAF) has its own planning factors and guidelines, as shown in Table 1-1. Table 1-1 shows the planning factors for potable and non-potable water and their uses presented in the Air Force Handbook for Civil Engineer Bare Base Development (2012). Air Force standards divide the water use into the type of water treatments, Basic Expeditionary Airfield Resources (BEAR), and fixed water treatment plants. The treatment distinction is made based on the robustness of the FOB. BEAR assets are used at bare bases or less established bases, while a fixed water treatment plant may be constructed on a more permanent base. Research has shown that the actual usage of water at FOBs ranges from 50.4-130.2 liters per capita day (lpcd) but recommends using 113.5 lpcd as a planning factor (Anderson 2013). For reference, an American citizen's average usage is 310.4 lpcd (Dieter and Maupin 2017).

Table 1-1: Water Use Planning Factors (USAF 2012a)

Functions	Water Usage (lpcd)	
Potable Water	BEAR assets	Fixed Water Treatment
Drinking	15	15
Personal Hygiene	11.5	11.5
Shower	11.5	57
Food Preparation	15	19
Hospital	4	7.5
Heat Treatment	4	4
Potable Subtotal	61	114
Non-potable	BEAR assets	Fixed Water Treatment
Laundry	19	53
Construction	7.5	7.5
Graves Registration	2	.75
Vehicle Ops	2	6.8
Aircraft Ops	7.5	11.3
Firefighting	7.5	15
Loss Factor (10%)	7.5	19
Non-Potable Subtotal	53	113.35
Total	114	227.35

1.2 Concerns with Water Supplies

Water for the contingency environment is obtained in three primary ways: 1) potable, bottled water transported into the FOB by supply convoys or airlifts, 2) using the host nation's water infrastructure, or 3) treating water from wells or surface waters (Lombardo 1998). Each of these sources has advantages and disadvantages, as mentioned previously.

When considering possible water sources, it is necessary to consider several factors. For example, is there enough available source water to provide for the FOB? And, is there enough water flow to reduce the possible impact of a toxic contaminant? Sources of pollution, such as landfills, sewage discharges, or oil refineries, near the water source should also be considered. It is also a good idea to look for visible water contamination (dead animals or vegetation, unnatural colors, oil slicks, or excessive algae growth) or obtain information from local populations. These are just some of the water supply threats; however, site and threat evaluation are outside the study's current scope.

1.2.1 Bottled Water

Currently, water transport is around 51% of the convoys moving throughout the theater (Council 2014). On average, there is one casualty every 50 supply convoys in Afghanistan (Moore 2011). Therefore, reducing the number of convoys needed for water resupply would significantly reduce the number of casualties. General Conway estimated that purifying water instead of transporting it could take over 50 trucks per week off the road in Afghanistan alone (Moore 2011). Needing fewer resupply convoys would translate into less fuel consumed, fewer troops required for protection, and reduce vulnerability to the US military. Bottled water may be the cultural preference of military members because it is perceived to be safer and can be procured easily and quickly, but it is also a massive source of waste. Many troops will only consume a portion of the bottle of water before opening a new bottle. Bottled water waste created such a problem that the US military's adversaries were planting improvised explosive devices in piles of empty water bottles on the side of roads (Moore 2011).

Bottled water is a considerable cost to the military; contracts cost anywhere from $0.53/liter to $0.92/liter while using a reverse osmosis water purification unit (ROWPU) has a cost of $0.008 to $0.03 per liter. Some projections show the United States military spent over $190 million on bottled water in Afghanistan during 2005 (Moore 2011). Bottled water transported in cases tends to deteriorate due to the heat experienced in these contingency environments. The plastic fails, and the water soaks the rest of the container, making it difficult to transport (Moore 2011).

1.2.2 Host Nation Water Supply

Water can be supplied to the US military's FOBs through host nation infrastructure. Due to the unknown nature of the infrastructure system, the US military requires the testing and treatment of this water to classify the water as potable (US Army 2005). The host nation may have different standards for water distribution; the infrastructure may have cross-connections or broken water lines unknown to the FOBs. In areas where military presence is resented, there is a potential for water terrorism to occur through the intentional addition of dangerous contaminants. Additionally, host nation infrastructure can only be used if it exists within proximity of the FOB. This solution is most feasible if the FOB uses host-nation facilities, the FOB is intended to become an enduring base, or the base is intended to be handed off to the host nation at the completion of the US mission (US Army 2005).

1.2.3 Source Water

The third traditional option of water for a FOB is source water. Source water could mean drilling wells or using a nearby lake or river. When drilling wells, it is recommended that multiple be drilled within the camp's boundary for the resiliency of water (USAF 2012b). If one runs dry or becomes contaminated, the FOB has a backup source for water ready for use. These can be used for non-potable water sources, or the water can be treated and disinfected for use as potable water. There are challenges with attempting to use source water. In arid regions, there may not be any standing or running water, such as lakes or rivers, near the FOB location. Additionally, the ground may be too hard to drill a well, or the well may run dry. Wells drying out is becoming more of a real threat to the Middle East's water supplies (USAF 2012b).

In arid regions such as the Middle East, it is common to go without rain or receive less than 20 inches per year (Joodaki et al. 2014). Since the Middle East's worst drought in 900 years started in 1998, water scarcity causes about half the countries in the region to consume more water than they receive annually (Powell 2016). Figure 1-1 shows the depletion of water storage in gigatons, using two different predictors (Gravity Recovery and Climate Experiment; CLM4.5) for Iraq, Eastern Turkey, and Saudi Arabia. These locations are all countries in which the US military operates. The water deficit in the Middle East increases the need for alternative options, specifically recycling water (Joodaki et al. 2014).

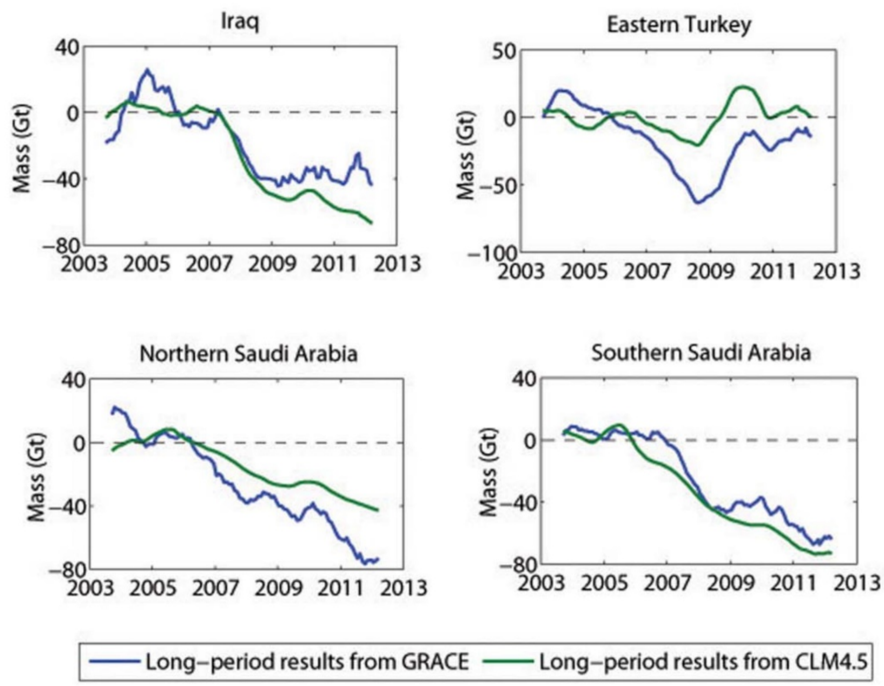

Figure 1-1: Water Storage Depletion base on GRACE and CLM4.5 predictors (Joodaki et al. 2014).

1.3 Water Scarcity and Other Threats

Sustainability has a plethora of definitions but is generally defined for water systems as continuing to meet the objectives of a group over time in the midst of maintaining social, environmental, and economic integrity (Loucks 1997; WCED 1987). Sustainability is fundamental when considering water systems, as groundwater depletion continues worldwide, and water scarcity becomes a more prominent problem (Konikow and Kendy 2005). Sustainable resources are increasingly valuable in locations considered hyper-arid, semiarid, and arid. Hyper-arid, semiarid, and arid environments are locations that receive little to no rainfall making the water sources in that region scarce. Figure 1-2 shows the climate areas of tropical, arid, temperate, cold, and polar locations, as well as the groupings created by spatial location and water table deficit. The groupings show the average water table deficit score. A lower score means less water table deficit, and a higher score means a higher water table deficit. This figure illustrates that many of the regions in which the US military operates have arid conditions with increasing water table deficits.

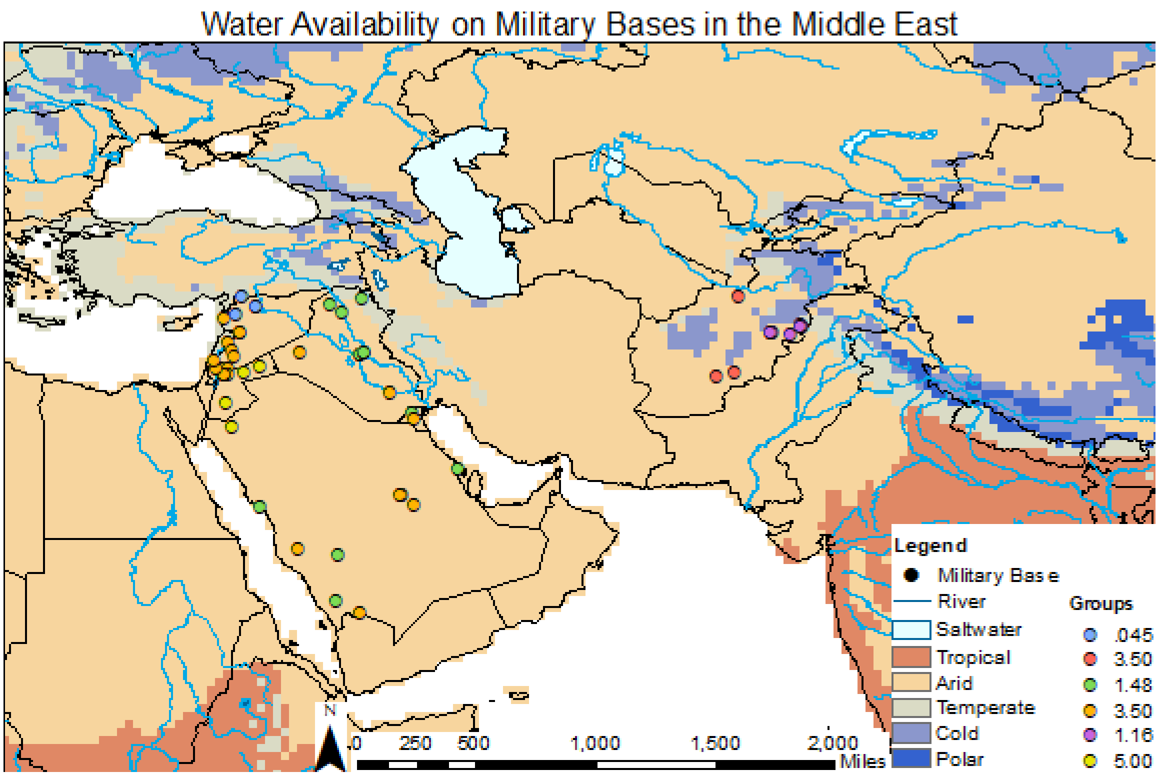

Figure 1-2

Water is essential for human life. Having a reliable water resource and water reuse or treatment system increases a FOB's resiliency and security. Resilience applies to this research in a few different ways. A base's resiliency is defined by "the ability to withstand and recover rapidly from deliberate attacks, accidents, natural disasters, as well as unconventional stresses, shocks, and threats to our economy and democratic system." ("Resilience" 2014). Resilience also applies to a base in the context of adaptive capacity and management. The number of people at a FOB can fluctuate over time, especially considering the possibility of mission change in a contingency environment. If the FOB is originally intended to last for 90 days and the mission changes or extends, a population increase is likely to happen. FOB size can vary from a small, austere camp with less than 50 people to enduring bases with over 10,000 people in the population (Lombardo 1998). Having a water source that can accommodate significant increases or decreases in population is essential. When water reuse can be factored into the water resource budget, accommodation for population size can be made more simple.

Obtaining water from off base sources presents the opportunity for water supply terrorism. Water terrorism has been used as a combat weapon for over 2,500 years (Gleick and Heberger 1994). Water supply terrorism can fall into a couple of categories. Biological or chemical attacks happen when a contaminant is introduced into a water supply with the intent of causing harm to human life (Gleick 2006). Denying physical access is another form of water terrorism. Denying physical access could happen if a militant group was to take control of a river denying water to a community downstream to create fear or political and societal objective.

In 2006, the Liberation Tigers of Tamil Eelam (Tamil Tigers) took control of waterway gates on the Maavilaru in Sri Lanka. The Tamil Tigers effectively cut off the water supply to 20,000 people in an attempt to gain power from the government of Sri Lanka (Dissanayake 2006). An enemy force could attack military supply convoys to prevent a FOB from resupplying bottled drinking water. On the other extreme, water terrorism could cause an oversaturation of water through the destruction of dams, levees, or reservoirs to flood a community and cause terror. Water delivered through convoys creates an additional security risk, and obtaining water from a single source, such as an on-site well or local stream, has inherent capacity or security challenges as well.

1.4. Research Focus

Previous research has been conducted on the sustainability of bottled water as a sole source of freshwater to the United States military in contingency environments (Moore 2011). Moore's study showed that bottled water is not a sustainable resource for potable water for US troops due to its costly resource supply chain and large amount of waste. Additionally, research has evaluated the selection of other potable water sources, such as the use of a Reverse Osmosis Water Purification Unit (ROWPU), wells, and local water networks (Binggeli 2017; George 2010). The research and optimization of alternatives conducted present advantages and disadvantages for all options.

This study will differ from the previous research by evaluating water reuse and recycling strategies. The reuse and recycling of wastewater could lower the demand for fresh potable water required by the US military. The study will evaluate greywater streams of wastewater.

The object of this research is to evaluate water reuse and recycling technologies for use at military FOBs in contingency locations. These alternatives will be analyzed in order to recommend a technology for water reuse/recycling to reduce the critical demand for freshwater. The technologies will be evaluated for cost-effectiveness, energy efficiency, and technology mobility with the following research questions addressed:

1. How should the tradeoffs (cost, energy, and mobility) of each system be evaluated in order to properly obtain an ideal decision?
2. Which technologies are able to reuse greywater to lower the demand for fresh water on FOBs?
3. Which technologies are best suited for use by the United States military?

This thesis will begin with an extensive literature review of the different water reuse, recycling, and treatment technologies. This literature review will also include literature pertaining to the current state of water use in the current military operational theater. The review will be used to obtain a list of the technologies' attributes and tradeoffs as these will be the criteria needed to evaluate the effectiveness of the technologies.

Next, the methodology used to determine the suitability of technologies will be presented. This methodology will include a presentation of how information was obtained, as well as how the research is limited. The methodology will include the explanation of the scale used for the evaluation and how each parameter of evaluation is taken into account for the presentation of the preferred technology.

The analysis and results will include each technology's evaluation using the information found through the literature review. Every technology will have the criteria assessed for effectiveness. The evaluation will include the utilization of the qualitative scale developed during the methodology section.

The final step will be to create a figure for the feasibility and effectiveness of each technology. This figure will be used to determine which technologies can be utilized by the United States Military, as well as which technology might best fit the contingency situation.

2. Literature Review

The purpose of this chapter is to discuss the existing literature, current technologies, and topics relating to the treatment of water for use by the United States Air Force (USAF) in relation to contingency and austere locations. First, this research will examine the regulations and requirements in place for the USAF's contingency water demands. Second, case studies will be analyzed for application to the needs of the USAF. Finally, the tradeoff criteria will be provided for analysis.

2.1 Definition of Potable Water

By definition, potable water does not contain chemical, microbiological, radiological, or other contaminants at levels that would make a person ill in the short-term (Water Education Foundation 2020). Following the DoD guidelines laid out in Technical Bulletin MED 557, water is required to be purified and disinfected before it can be considered potable. The US military must follow state and federal law, as well as host nation laws when it comes to water and wastewater regulations (US Army 2005). In areas of overlap, the more stringent requirement is followed.

2.1.1 Water Regulations

The requirements for water to be considered potable can be found in Table 2-1. This table shows the maximum level of contaminants allowed in potable water. The values in the table are categorized both by the amount of water to be consumed and the duration of consumption. These separate categories follow the concept that short period exposure to some contaminants is acceptable for human consumption, while a longer period of exposure necessitates far lower levels of contaminants. Additionally, because water sources can become contaminated and treatment systems need maintenance over time, the concentration of contaminants in the water is checked anywhere from daily to quarterly based on the type of contaminant and type of storage container (US Army 2005). For example, when potable water is stored in a field storage container (such as a water buffalo), it needs to be tested daily for chlorine residual. When potable water is distributed through a system, it needs to be tested monthly for coliforms, and when a Reverse Osmosis Water Purification Unit (ROWPU) is used, water needs to be checked quarterly for arsenic, cyanide, sulfate, and radiological contaminants. As a forward operating base's (FOB) water system stabilizes, water testing is needed less frequently.

Table 2-1: Potable water standards as defined by the Department of Defense. Table 2-1 is adapted from information found in TB MED 557 (2005).

	Use < 7 days		Use > 7 days	
	5 L/day	15 L/day	5 L/day	15 L/day
Physical properties				
Color (color unit)	50	50	15	15
Odor (threshold odor number)	3	3	3	3
pH	5 - 9	5 - 9	5 - 9	5 - 9
Temperature (^{o}C)	4 - 35	4 - 35	15 - 22	15 - 22
Chemical Properties				
Arsenic (mg/L)	0.3	0.1	0.06	0.02
Chloride (mg/L)	600	600	600	600
Cyanide (mg/L)	6	2	6	2
Lindane (mg/L)	0.6	0.2	0.6	0.2
Magnesium (mg/L)	100	30	100	30
Sulfate (mg/L)	300	100	300	100
Microbiological properties				
Coliform (#/100mL)	0	0	0	0
Chemical Warfare Agents				
Hydrogen Cyanide (µg/L)	6	2	6	2
BZ (Incapacitants) (µg/L)	7	2.3	-	-
Lewisite (arsenic fraction) (µg/L)	80	27	-	-
Sulfur mustard (µg/L)	140	47	-	-
Nerve Agents (µg/L)	12	4	-	-
Radiological (µgCi/L)	8	3	-	-

2.1.2 Water Requirements

Potable water is not required for every activity on a FOB. While potable water may be the preferred solution for all water needs, many activities can use fresh (non-potable) water, disinfected freshwater, or brackish/seawater. Brackish or seawater can cause corrosion; therefore, it should only be used in certain situations as defined in Table 2-2, and even then, sparingly. Activities may use higher quality water, but not lower quality. Table 2-2 shows which activities on a FOB require which quality of water. Potable water is the highest quality and decreasing in quality going down the chart.

Table 2-2: Water use activities sorted by water quality. Information is adapted from TB MED 557 (2005).

Water Quality	Acceptable activities
Potable water	• Drinking water • Dining facility operations such as food washing • Brushing teeth • Medical treatment • Ice production for food preservation and cooling • Water hose and pipeline testing and flushing • Photo-processing (for quality control)
Disinfected freshwater (non-potable)	• Centralized hygiene (field showers) • Decontamination of personnel • Retrograde cargo washing • Heat casualty body cooling • Graves registration personnel sanitation • Well development
Freshwater (non-potable)	• Vehicle coolant • Aircraft washing • Pest control • Field laundry • Concrete construction • Well drilling
Brackish and seawater	• Vehicle washing • Electrical grounding • Fire fighting • Chemical, biological, radiological, nuclear, and explosives (CBRNE) decontaminant

2.1.3 Water Demands

The United States military has been present in the Middle East and other arid regions for over 30 years (Bowman 2008). The US has over 80,000 military personnel in these regions, with a consistent presence projected into the foreseeable future. (USAFacts

2020). This military presence means that a sustainable water supply will be required to maintain a FOB's security and resiliency.

With the population of FOBs varying widely and changing frequently, water demands are measured in liters per capita day. This method makes it possible to calculate the water demand for each FOB based on population. As previously shown in Table 1-1, water demands for a FOB can be broken down by activity and potable versus non-potable water. The baseline shown in Table 1-1 is the accepted standard by the USAF, but through previous research done by Anderson (2013), it has been found that the baseline can be larger or smaller than the USAF's standards. This research will follow the USAF's baseline standards.

2.2 Water Reuse

The idea of water reuse or recycling has become more popular around the world over the last century. There are two main types of potable water reuse: direct and indirect (Asano 2007). Asano defines direct potable reuse (DPR) as reuse that involves treatment and distribution back to the public without an environmental buffer. Indirect potable reuse (IPR) treats the water to be returned to the environment (lake, river, or groundwater aquifer). After the water is returned to the environment, it is treated to drinking water standards and distributed to the public. Along with these two water reuse strategies, there is "de facto" water reuse. De facto water reuse happens when wastewater is treated by a community and returned to the environment. Later, a community downstream then draws water (containing treated wastewater) from that source (National Research Council 2012). This research will focus on the use of DPR for FOBs. IPR is not useful due to the austere location of FOBs and the contingency and agile intent of a FOB. A few countries, especially in water-scarce regions, have adopted water reuse both direct and indirect.

2.2.1 Direct Potable Reuse

When using DPR as an option for a water source, some considerations need to be addressed. For one, DPR does not have the best public perception, often termed the "ick" factor (Asano 2007). There is a reluctance to accept that water that has once been used and contained contaminants can be used for potable water after treatment. This perception could be avoided by educating customers on DPR's implications or making sure that the water which has been disinfected is used for activities other than drinking. Additionally, it is critical to certify that DPR's technology is advanced enough to ensure that the reclaimed water consistently meets the correct standards for potable water (Asano 2007).

2.2.2 Case Studies – DPR

In Windhoek, Namibia, DPR started in 1968 due to the water table's depletion around the city (Lahnsteiner et al. 2018). The city continues to blend treated wastewater with potable water before distributing it to its citizens. After multiple upgrades, this system provides 30% of the city's potable water, usually and up to 50% during times of drought (Asano 2007). There are three types of safety barriers that filter harmful contaminants from the water. These three barriers are non-treatment barriers, treatment barriers, and operational barriers. Non-treatment barriers separate domestic sewage and industrial effluent. The purification systems form treatment barriers, and non-treatment barriers are used only when the treatment barriers do not work to the correct standards (Lahnsteiner et al. 2018). Windhoek produces drinking water from a mixture of reclaimed domestic sewage and groundwater. Windhoek uses a non-treatment barrier to separate domestic and industrial effluent. Only domestic effluent can be used for DPR. The process used by Windhoek is seen in Figure 2-1. The domestic effluent put through carbon dosing, pre-ozonation, enhanced coagulation and flocculation, dissolved air flotation, dual media filtration, main ozonation, biological activated carbon filtration, granular activated carbon adsorption, ultrafiltration, and disinfection with chlorine and stabilized with caustic soda (Lahnsteiner et al. 2018).

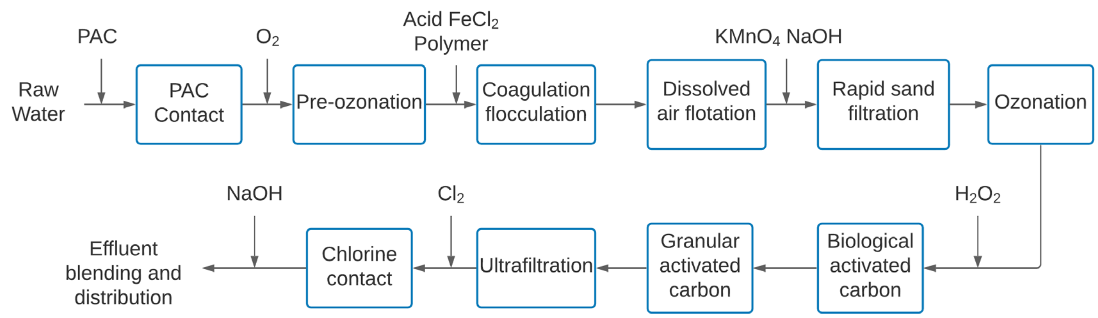

Figure 2-1: The City of Windhoek's water treatment process (Asano 2007).

The city of Denver, Colorado, conducted a study with DPR from 1985 to 1992. This study provided information to consider DPR a viable option to supply potable water to satisfy Denver's future water needs (Asano 2007). This study evaluated the health effects, operations, and maintenance processes, as well as the different treatment options. The constructed test facility used sedimentation, recarbonation, filtration, UV irradiation, carbon, adsorption, reverse osmosis, air stripping, ozonation chloramination, and ultrafiltration (Asano 2007). Once this study was completed, the use of DPR was discontinued. Water was not in such demand that DPR is imperative to providing water to Denver. This case study was done to assess the benefits, risks, and effects of DPR, as well as prove that it is possible for society (Lauer et al. 2015).

Singapore started looking into water reuse in the 1970s. Before this, Singapore was heavily reliant on Malaysia for fresh potable water. In the early 2000s, Singapore achieved the creation of NEWater (reclaimed water) plants (Ghernaout et al. 2019). There are now four plants across Singapore that supply 30% of the country's water. This percentage is expected to rise by 25% by 2060 (Ghernaout et al. 2019). These NEWater plants use sedimentation, activated sludge, microfiltration, ultrafiltration, reverse osmosis, and ultraviolet disinfection (Asano 2007). With these treatments, the water produced exceeds the World Health Organization requirements for drinking water (Ghernaout et al. 2019).

The DPR plants discussed in these case studies are large scale (providing 3.8-20.8ML/day) (Asano 2007). The systems work with wastewater from a large population and provide treated, potable water for many people. These case studies use DPR systems that require ample space to build and operate. The space on a FOB is in high demand, meaning that the smaller the system, the better. The research performed for this study investigates the use of small-scale technologies for use in austere locations.

2.2.3 Indirect Potable Reuse

Indirect potable reuse happens after wastewater is treated and released into the groundwater, river, or streams. IPR can happen unintentionally, as wastewater can enter the raw water source elsewhere and be pulled into a treatment plant for drinking water (Jansen et al. 2007). This process is unplanned IPR and happens frequently. Planned IPR is the intentional augmentation of highly treated wastewater into surface waters, reservoirs, or groundwaters. The water is then pulled from these water sources and treated for potable water use (Asano 2007).

2.2.4 Case Studies – IPR

Singapore is very water-scarce; this is primarily due to the high population density. As a result, Singapore takes advantage of both direct non-potable water reuse and IPR. In 1999, Singapore began developing IPR facilities to augment the potable water storage (Asano 2007). These facilities are membrane-based and use microfiltration, reverse osmosis, and ultraviolet disinfection processes (Asano 2007). This water is the effluent of a sludge treatment process, treated through the treatment facility, and deemed potable after treatment. This water is then mixed with the fresh potable water in a raw water reservoir. The water from the IPR process makes up 15% of the water used for drinking water (Asano 2007).

In Southeast Queensland, Australia, the idea of IPR was first accepted in 2005 to mitigate the water demands during droughts (Traves et al. 2008). The IPR treatment includes membrane filtration, reverse osmosis, advanced oxidation, stabilization, and disinfection (Traves et al. 2008). While the reuse of water for industrial purposes was not unique, the use of IPR for potable water supplies was never considered before. This water will make up 10% of the region's potable water supply.

San Antonio, TX launched an IPR process in 1996 to supplement the Edwards Aquifer's water supply (Hartley 2006). Water from San Antonio's reclamation plants is used for agricultural and industrial needs, as well as groundwater recharge (Eckhardt and Clouse 2006). The reclaimed water from these plants is discharged into the San Antonio

River and Salado Creek to augment the groundwater. The water from these rivers is then collected and treated for potable water (Hartley 2006). This IPR process has created almost a complete water reuse loop for the city of San Antonio (Eckhardt and Clouse 2006).

IPR is useful for large cities or locations with an abundance of surface water. These case studies look at three locations with a large population, space for large treatment plants, and surface water for reclaimed water to return. IPR is not feasible for use on a FOB due to the austere and agile environments. IPR is designed for a much larger population and has a more substantial space requirement than a FOB has or can provide.

2.3 Small-Scale Reuse Systems

The systems evaluated in this research are direct potable reuse systems that can treat enough greywater to provide non-potable water for a 500 person FOB. These systems are small enough to be moved if needed, unlike the systems discussed in the case studies before. The water may technically be considered potable at the end of the treatment but will be used for non-potable uses to mitigate the "ick" factor. The intent of these water reuse systems is not a closed-loop; the water will not be used to meet the total demand for water on a FOB but, instead, to mitigate the need for freshwater.

2.4 Technology Tradeoffs

The technologies used to treat water for potable reuse will need to be evaluated under three criteria: cost, energy efficiency, and mobility. These parameters will enable the evaluation of which technologies will be best suited for use by the USAF. There is no perfect system; each technology will have compromises for each tradeoff. For example, a very energy-efficient technology may be more expensive due to the materials or processes needed for the technology. There is a push-pull relationship between the three criteria, making it impossible to find a perfect solution.

2.5 Summary

This literature review covers what makes water potable, the water requirements for water on a FOB, the regulations the United States military follows, and the water demands of military FOBs. The idea of water reuse is presented to provide additional water or reduce freshwater demands on a FOB. This research is not presented as a closed-loop system as it is not intended to meet the total water demand of a FOB, only to reduce water demand. Many case studies of direct and indirect water reuse are assessed and evaluated for applicability to the US military's needs. After evaluating these case studies, it is determined that direct potable water reuse is ideal for military use. The direct potable reuse case studies in this research are larger scale than beneficial for FOBs, and therefore need to be reduced in size, or other technology must be used.

3. Methodology

This chapter describes the methodology used to analyze the evaluation criteria for the technologies. These three criteria: cost, energy efficiency, and mobility provide the basis for assessing each water reuse technology for the application of small-scale use in the United States military. The three evaluation criteria determine which technologies will help reduce the need for fresh potable water on forward operating bases. This chapter will also discuss the process in which each technology was found and selected for analysis. Each evaluation criteria will introduce the scale of qualitative ranking and how it was obtained for each.

3.1 Evaluation Criteria

The three criteria (cost, energy efficiency, mobility) are used to evaluate the technologies' applicability. Each technology is evaluated with the objective of low cost, high energy efficiency, and high mobility. It is necessary to keep in mind that there is no perfect solution. Focusing on one of the three tradeoffs will result in a sacrifice of the other criteria. For example, a highly energy-efficient technology may have a higher cost and be less mobile. The three criteria evaluation parameters have been determined through the review of previous research.

3.1.1 Cost

Cost is traditionally evaluated using the United States Air Force's definition of life cycle cost. Life cycle cost encompasses the total cost of a system over its full life. These costs include purchasing, transport, operating, supporting, and disposing of the equipment ("AFMAN 65-506" 2019). The purchase cost, or unit cost, is the total cost of all the components that make up the system. This purchase cost is the baseline cost for a unit. The transportation cost includes the cost of the sortie or convoy used to get the unit to its location, as well as the cost of the fuel used for the vehicle transport needed. The operational costs include the cost of any fuel, energy, or electricity needed to operate the system for its lifetime. Support costs, or maintenance costs, are the costs incurred by any scheduled maintenance needed over the time the system operates and any costs for unexpected maintenance that may be required over the system's life cycle. Finally, the disposal costs include any cost incurred by the dismantling, removal, or disposal of the system at the end of its lifetime.

Due to the criteria used for evaluation in this research, some of these costs are accounted for in other research aspects. The operational costs will be accounted for in the energy efficiency parameter. The transportation and disposal costs are evaluated in the mobility criteria. Therefore, the only cost used for evaluation is the purchase cost.

3.1.2 Energy Efficiency

Energy efficiency is important to the operation of water treatment technology. The goal of energy efficiency is to reduce energy use without sacrificing the system's output. In this research, that refers to using less energy to create the same amount of recycled water. Having high energy efficiency reduces the amount of energy needed to complete the treatment of water. This energy reduction can decrease the cost of operation and decrease the environmental impact of the system by lowering the Greenhouse gas emissions (U.S. EPA 2013). Relationships in the energy-water nexus dictate that reducing water use will also help with the reduction of energy use, resulting in higher efficiency of energy (and water) use (Copeland 2014).

For this research, energy efficiency is evaluated by the input energy and recycled water output over a day. While it is impossible to achieve a perfect efficiency rate, this research aims to obtain a high energy efficiency rating (U.S. EPA 2013). These energy efficiencies have been taken directly from research on these systems. While not all systems that have been evaluated have the same units, it is possible to normalize these efficiencies and convert them to a standard unit for all technologies. Normalizing and converting these efficiencies causes some loss in efficiency as fuel conversion to electricity incurs an efficiency loss. The efficiency of the process in which the fuel is converted to electricity depends on the type of fuel used, which accounts for the normalization of the technology's energy efficiency.

3.1.3 Mobility

Mobility is the most subjective of the three criteria. The mobility of a water treatment system is not typically an evaluated detail of a system. Usually, once a system is placed, it does not need to be moved. However, mobility becomes essential, particularly in this research, when in contingency locations. As discussed before, the United States military has unique requirements for building a forward operating base. The ability to bring in a water treatment technology immediately and remove the system when it is no longer needed in that location becomes essential. The military's mission requires agile resources that can be set up or torn down in a short period. The capability to continue to utilize the system after the removal or transportation to a new location increases the military's readiness and ability to respond to any situation.

This research evaluates the mobility of water treatment technology by looking at three aspects. These aspects are the size of the technology, the ease of transportation, and the technology's permanence. This research looks at providing for a 500-person FOB. This number was chosen for the mid-range FOB size. The technology's size is determined by the space a technology uses and the weight of the technology. The size directly impacts the transportation aspect due to the number of pallets needed to transport the technology. Transportation is evaluated by looking at two factors. These two factors are the number of pallets needed to deliver the system and the method of transportation. These transportation methods may be a convoy, airlift, or ship. Transportation is simplified into the number of pallet spaces taken up on an aircraft during transportation. A pallet is traditionally 2.75m x 2.3m and has a capacity of 4535 kg (Globid 2019). Depending on the aircraft, the number of pallets spaces ranges from 6 on the C-130 to 36 on the C-5 (USAF 2018). The final part of the mobility criteria, permanence, is evaluated by the ease of set up and tear down and if the technology can be used multiple times after removal.

3.2 Discovering Technology

The data used in this research has been gathered through an extensive review of previous research. These technologies and their data have been gathered using specific keywords over multiple scholarly article databases. Each technology's tradeoffs have been gathered from this review and reworked to align with the correct units and normalized for the correct number of people. From this point, the evaluation and analysis of each technology have been performed to present a preferred solution to best benefit technology.

3.2.1 Process

The process for discovering technology comes from the extensive literature review performed for this research. Multiple databases were searched for technologies that could be beneficial for greywater reuse at a small scale. The research databases primarily used for information were Google Scholar, Elsevier, and ScienceDirect. These technologies found first evaluated for basic ability to treat water, specifically to meet the standards required by the Department of Defense on harmful chemicals (Table 2-1). Part of this evaluation includes determining if the system can be used to treat greywater. For the purpose of this research, the greywater characteristics are assumed to meet the ranges laid out in Table 3-1. Greywater properties are shown in ranges due to the possibility of variability (US Army 2011).

Table 3-1: Ranges of contaminants in greywater. Table 3-1 is adapted from PWTB 200-1-101 (2011).

Properties	**Range**
Temperature (C^o)	21.6 - 28.2
pH	7.6 - 8.6
Chemical Oxygen Demand	77 - 240
BOD	26 - 130
TSS	7 - 207
Turbidity (NTU)	43 - 76
NH4-N	0.02 - 0.42
NO3-N	0.02 - 0.26
Total N	3.6 - 6.4
Tot-P	0.28 - 0.779
Sulfate	22.9 - 59.59
Chloride	9 - 20.54
Hardness	144
Alkalinity	158
Ca	99 - 100
K	5.9 - 7.4
Mg	20.8 - 23
Na	44.7 - 98.5
Total Bacterial Pop. (CFU/100 mL)	4.0×10^7 — 1.5×10^8
Total Coliform (CFU/100 mL)	2.8×10^7

After ensuring that the technology can meet the functional requirements, the technology has been evaluated to ensure that it is possible to meet the FOB's water demands. This need requires that the water production meets the Air Force's baseline for water demands (Table 1-1). The technologies that met these initial requirements were then evaluated for cost, energy efficiency, and mobility.

3.2.2 Keywords

Due to the immense impact the literature review and previous research have on this research, key search words were developed to streamline the research process. These keywords progressed throughout the research and have been compiled into Table 3-2. Table 3-2 breaks out the terms used to search into keywords and the words associated with them. These words, variations, and combinations of each have been used to search databases for articles.

Table 3-2: Keywords used for research.

Water	Energy	Cost	Mobile	Other
Reuse	Efficiency	Efficiency	Technology	Sustainability
Greywater	Demand		Water Treatment	FOB
Technology				Deployment
Potable				Remote
Recycle				Emergency
Treatment				Military
Recovery				

The keywords resulted in seven candidate technologies. These seven technologies are described in Chapter 4 before being evaluated in Chapter 5.

3.3 Process of Evaluation

After the initial evaluation to determine the technologies for this research, each technology will be examined further. Using the literature available from these databases, the technologies are individually researched to find the data needed for evaluation. This data includes each system's cost, the size of each system, how much water each system can provide, and any other pros or cons of each system. This data is attributed to the three criteria: energy efficiency, cost, and mobility. From this point, each technology receives a score to determine its effectiveness.

3.4 Summary

The technology alternatives for direct water reuse have the potential to provide a new option for supplying water to the United States military. Each technology has its pros and cons, and there is no perfect system. The evaluation parameters, cost, energy efficiency, and mobility have provided the framework to determine the preferred water reuse technology. This chapter describes the methodology used in this research to determine the preference. Each evaluation criteria has been described, and the process for doing so is established.

4. Technologies for Evaluation

When utilizing the process and keywords previously mentioned, seven technologies were discovered for analysis. Each of these technologies has been researched for the use of treating water. In this chapter, each technology's background and characteristics have been laid out to understand each technology before final analysis better. Having this background knowledge on each system will better allow for understanding each system's pros and cons. These pros and cons may not fall into the three evaluation criteria. Still, they would impact the decision to use these systems.

4.1 Reverse Osmosis Water Purification Unit

The U.S. military has used the Reverse Osmosis Water Purification Unit (ROWPU) to purify source water since 1979 (US Army 1982). Typically, the ROWPU is used to purify ground and surface water, including well water or even ocean water. Depending on the size of the unit and quality of water, ROWPUs can produce anywhere from 2,271 to 11,355 liters of water per hour (Nicoll 2001) or up to 250,000 liters/day. This research uses the smallest ROWPU unit at 49,967 liters/day. These units can be mobilized on pallets, trailers, or ships. The typical ROWPU has a rectangular, metal frame, weighs around 3,400 kg, and takes up 18 cubic meters ("ROWPU" 2011). The ROWPU utilizes coagulation, multimedia filtration with ion exchange, cartridge filtration, reverse osmosis, and disinfection ("ROWPU" 2011). Each ROWPU can be used for about 11 hours before the system needs to be backwashed for filter maintenance. This backwash process produces 3,785 liters per cycle, meaning 7,570 liters of backwash per day. ROWPUs are expensive units with a purchase cost of around $750,000 and a combined filter replacement cost of over $15,000 (Binggeli 2017; "ROWPU" 2011). A ROWPU unit requires the use of a 30kW generator to operate.

Figure 4-1: Reverse Osmosis Water Purification Unit (USAF 2011).

4.2 Transportable Ultrafiltration Membrane System

French researchers have created a transportable ultrafiltration (UF) pilot water treatment plant. This plant is for the use of mobile firefighters to provide drinking water. Ultrafiltration is a process that uses membranes and a pressure gradient between the sides to filter the water. At about $13,000, this plant comes in an enclosed aluminum crate with four UF modules to filter water and a chlorine tank for disinfection (Barbot et al. 2009). Due to this plant's small size, it can only treat 23,984 liters/day of water, but this plant weighs 150 kg, is small enough to be carried by four people, and takes up less than 1 m^3 (Barbot et al. 2009). The weight and size of this unit make it incredibly mobile, but the treatment operations have been significantly simplified to maintain this. For this plant to process water, it has a power requirement of 0.6 kW, provided by a small electric generator (Barbot et al. 2009). A French firemen team is currently using this plant in Marseille for rescue missions in extreme conditions (Barbot et al. 2009).

Figure 4-2: Transportable ultrafiltration system used by French firefighters (Barbot et al. 2009).

4.3 Package System for Emergency Water Supply

In South Korea, Young Kyu Park developed this package system as a mobile treatment system for water during emergencies. The idea for this system comes from the water service interruptions that commonly happen during natural disasters (Park et al. 2015). This system uses a combination of ultrafiltration using a pore control fiber filter, RO process, and UV disinfection (Park et al. 2015). These processes can fit into a 6 m container, with a second container for the energy supply, maintenance equipment, and other needed equipment. Altogether, this system can treat 30,000 liters/day of water only using 2.1 kW (Park et al. 2015). This energy requirement means that a small generator that provides 5 kW would be sufficient for this system.

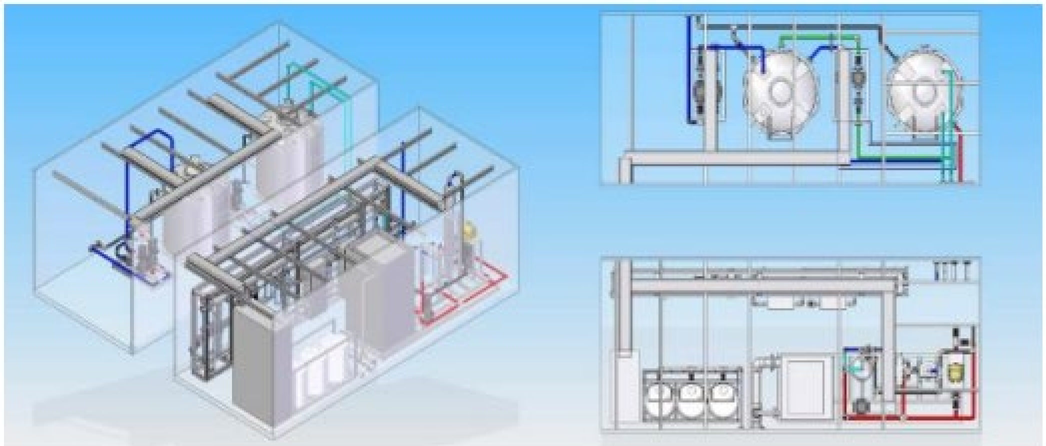

Figure 4-3: Package Unit diagram to include the second container with maintenance equipment and energy supply (Park et al. 2015).

4.4 Micro Hydraulic Mobile Water Treatment Plant

The Micro Hydraulic Mobile Water Treatment Plant (MHMWTP) was developed in Indonesia. Developing this plant was primarily done to provide emergency water to people after natural disasters that cause damage or contamination to water treatment and distribution systems (Garsadi et al. 2009). The MHMWTP has since been utilized by the Indonesian Army, public works departments, local governments, and multiple private companies. The system is simple enough that untrained personnel can operate it (Garsadi et al. 2009). The MHMWTP is a series of treatment processes similar to a conventional process (coagulation, flocculation, sedimentation, filtration, granularly activated carbon, and disinfection), which have been placed onto a truck bed. These processes require less than 5kW of power in total and can produce 330,000 – 440,000 liters/day (Garsadi et al. 2009). Because of this system's size, it is possible to transport on a truck or cargo plane

(C-130) (Garsadi et al. 2009). The operational cost for these systems is about $22/day (Garsadi et al. 2009).

Figure 4-4: Micro hydraulic mobile water treatment plant used in Aceh, Indonesia (Garsadi et al. 2009).

4.5 AdvanTex AX Greywater

This system was developed by Orenco Systems and treats greywater to acceptable standards for reuse. This technology has been used around the world for multiple applications. The system is a fully enclosed, prepackaged unit that can treat up to 45,425 liters of greywater per day (Orenco Systems 2017). At 4.2 x 2 x 1.5 m, this system is small enough to be transported on a semi-truck or airlifted into austere locations or moved after placement (Orenco Systems 2017). The processes used for treating the greywater are filtration with textile media and UV disinfection (Orenco Systems 2017). This treatment process uses less than 2kW per 3,785 treated liters of water (Orenco Systems 2017). These systems can be priced anywhere from $5,000 to $30,000 (Austin n.d.).

Figure 4-5: AdvanTex AX Greywater system (Orenco Systems 2017).

4.6 Mobile Constructed Wetland

A mobile constructed wetland and drinking water unit have been used to treat water at remote tourist sites in Europe. This treatment system uses a semi-trailer containing three substrate layers to filter wastewater; wastewater is pumped in from one tank into the top of the trailer to filter through the substrate (Lakho et al. 2020). This system weighs 21,772 kg to keep it under the road weight regulations and be mobile (Lakho et al. 2020). Because this system uses gravity to filter the greywater and a simple pump to transport the water to the top of the wetland, the system uses very little energy (Zraunig et al. 2019). These systems use a flowrate of 10,085 liters/day and have a hydraulic retention rate of 1-2 days (Zraunig et al. 2019).

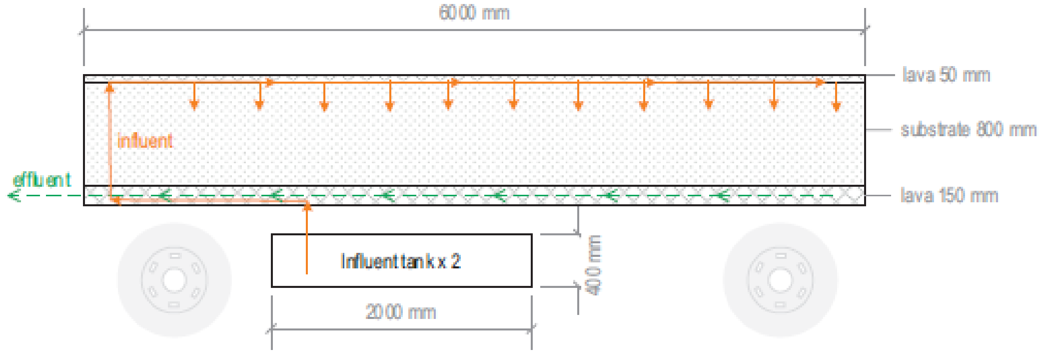

Figure 4-6: Diagram of mobile wetland (Lakho et al. 2020).

4.7 Aerated Cells Mobile System

The aerated cells mobile system was initially developed to treat winery wastewater, which contains a high chemical oxygen demand (COD), biological oxygen demand (BOD), and a high level of total suspended solids (TSS) (Litaor et al. 2015). This system uses rotating screens or settling tanks with clay-polymer nanocomposites and multiple aeration units with tuffs to reduce TSS, COD, and BOD (Litaor et al. 2015). This system is small enough to fit on the back of a truck, meaning this system is transportable either by truck or cargo plane. The treatment of water through this system is found to have a cost of about $.0075/liter or, as a total, between $35,000 and $45,000 (Devesa-Rey et al. 2011). This system uses a flow rate of 5,000 liters /day and a retention time of 1.61 days (Litaor et al. 2015).

Figure 4-7: Aerated cells mobile system being placed at a winery for use (Litaor et al. 2015).

4.8 Summary

These seven technologies can be used to treat water for reuse at military FOBs in contingency locations. Each of these technologies has its pros and cons. With the information discussed in this chapter, an analysis will be conducted to recommend the best technology. The data provided will be used to create a radar chart for each technology. The best overall technology will be decided using these radar charts.

5. Results and Analysis

The seven technologies and their specifications are shown in Table 5-1. These numbers come from the literature review of the reuse systems; therefore, some information is unavailable, denoted by "Unavailable". All information for these systems comes from previous research or manufacturer specifications. With these specifications, the tradeoffs of cost, energy efficiency, and mobility can be evaluated. The specifications of power and water production are used to evaluate energy efficiency, size and weight for mobility, and price for the cost. The numbers in this table are the specifications for a single unit of each technology. By increasing the number of units, the minimum amount of non-potable water can be met. The minimum amount of non-potable water is found by taking the total non-potable water amount from Table 1-1 and multiplying it by 500 for the minimum amount of non-potable water needed for a 500-person community (7,000 gpd). The other specifications for each technology are multiplied by the number of units to meet the non-potable water demand.

Table 5-1: Specifications of each technology found through the literature review.

	Number of Units	Power (kW)	Water Production (L/day)	Unit Price (U.S. dollar)	Size (meters)	Weight (kg)	Number of Pallets/Unit
ROWPU	1	30	49,967	750,000	5.5x2.5x2.5	3,402	1
UF Membrane System	2	0.6	23,984	13,000	1.1x0.9x1.1	150	1
Package System	1	0.0875	30,000	Unavailable	6x2.5x2.5	Unavailable	3
MHMWTP	1	5	330,000	Unavailable	4.2x2x1.5	Unavailable	2
AdvanTex AX	1	18	45,425	30,000	12.8x2.1x2.5	5,443	5
MCW	3	5	10,085	9,000	14.6x2.6x2.6	21,772	6
Aerated Cells	6	1.5	5,000	45,000	14.6x2.6x2.6	Unavailable	6

The data from Table 5-1 is normalized to provide enough water and used to create radar charts for each of the technologies. Some systems needed multiple units to reach the non-potable water demand. The U.F. Membrane System needs two units, the Mobile Constructed Wetland needs three units, and the Aerated Cells needs six units. All other systems only need one unit. The need for multiple systems is accounted for in Figure 5-1, which shows the radar charts developed from the information collected. These charts can be used to help determine which technology is the best fit for each situation. The colored points on the charts are associated with the three evaluation criteria. On the radar chart, a larger encompassed area denotes a better technology. Therefore, a lower cost and size are on the outside of the radar chart, but a higher efficiency is on the outside edge. Along with this, the charts can be used to see if a technology's tradeoffs are applicable for the situation. For example, if a technology needs to be stationed permanently, the mobility criteria can be ignored.

The radar charts can help decide which technology best fits the situation from the data collected on each technology. With the use of Figure 5-1, it is possible to visually determine which technology is the best fit for each situation. Suppose a system does not need to be moved after its placement; in that case, the best option might be the mobile constructed wetland. The mobile constructed wetland is a system on the larger side but has a relatively low cost and power consumption with comparable water production. Another example would be if the system needs to be moved with the troops during missions. This would lead to the decision of a highly mobile, low power requirement system, or the transportable ultrafiltration membrane system.

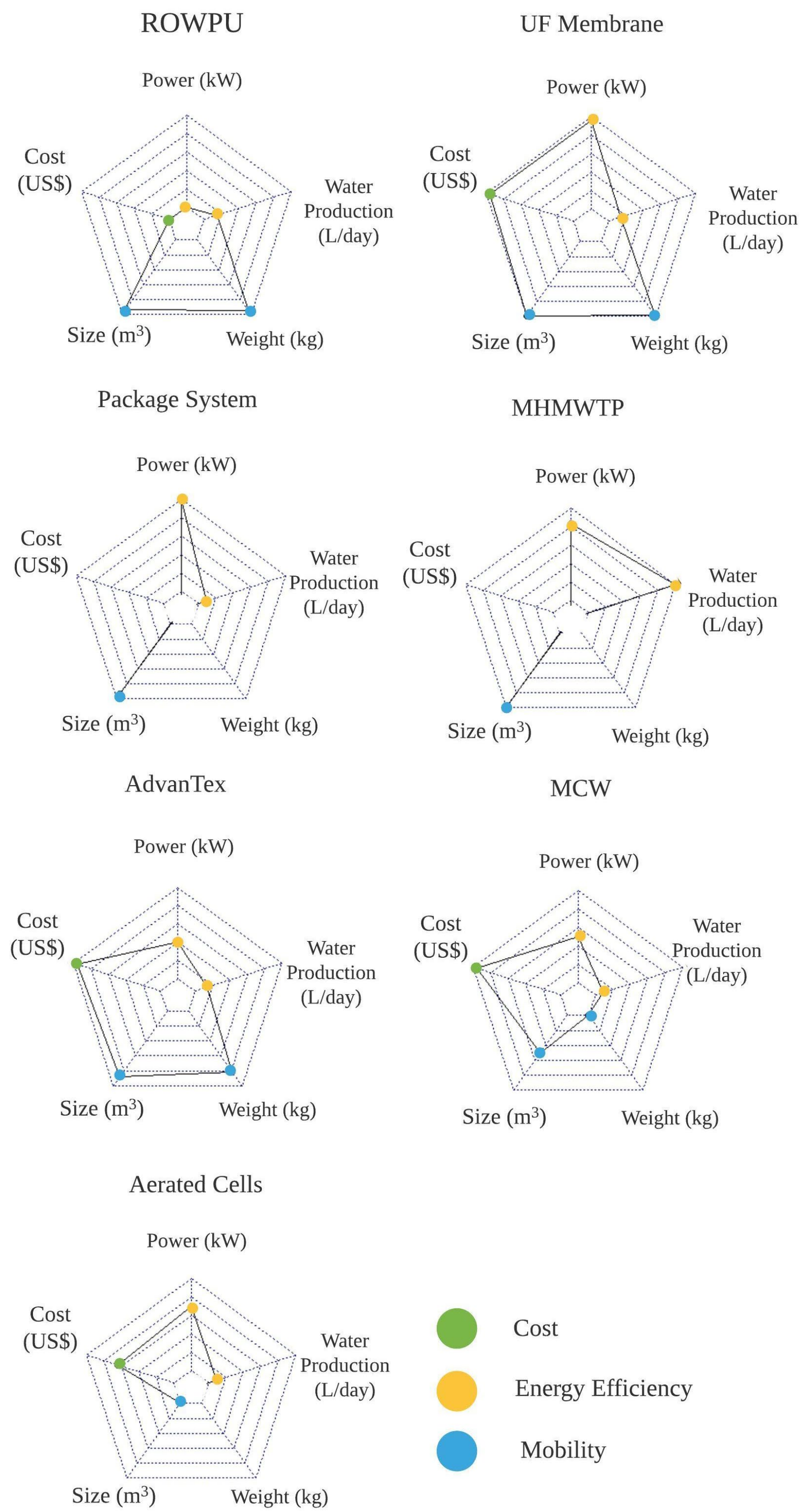

Figure 5-1: Tradeoff Radar Charts

The U.F. membrane or the AdvanTex unit appears to be the best treatment options based on the radar charts. The radar charts show the area enclosed by the dots is the largest. The only drawback for these systems is their low water production. The water production for these units is similar to all of the other units, except the MHMWTP. With more data available, the MHMWTP has the potential to be the best technology, depending on the cost and weight of the system. The aerated cells system has a large size due to the number of units needed to provide enough treated water. The system also has a low water production and a higher cost and power requirement than most other systems. These results make the aerated cells system less desirable for use.

Comparing the ROWPU, the current technology choice of the US military, to the other technologies in this study shows that it may not be the best choice for water reuse. With more research into these newer technologies, it may be beneficial to choose a different option. The AdvanTex AX Greywater unit only treats greywater to a reusable standard, not to potable standards, which makes it useful for water reuse, but not for potable water. The U.F. membrane units treat the water to potable standards and are extremely portable. This would be beneficial to a military contingency environment. These units would need to be tested in the current military theater to determine the durability of the systems. The MHMWTP could be the best choice instead of the ROWPU, but further research and testing would need to be completed before a decision could be made.

6. Conclusions and Recommendations

This study examined seven water reuse technologies (ROWPU, UF membrane, Package System, MHMWTP, AdvanTex AX Greywater, MCW, Aerated cells system) for the use of the US military. Water reuse presents a fourth option for providing water to the U.S. troops in austere locations, even if the water is only reused for non-potable uses. At the very least, water reuse would mitigate the need for fresh water in these environments. This mitigation would allow the freshwater to be used for potable uses and recycled water for non-potable uses.

Using the three criteria (energy efficiency, cost, and mobility), each system was evaluated to assist in determining the best technology for each situation. Radar charts created in this study offer a way to visually communicate the results and allow a decision-maker to select a technology based on the needs of the user by weighting each criterion. With this information, it can be made for each community or emergency situation. Using the information found through the literature review, a decision can be made that the overall best systems for use are the U.F. membrane or the AdvanTex systems. These systems are low cost, have a low power requirement, small in size, and have a low weight. The U.F. membrane systems are smaller in size and weight than the AdvanTex system, but multiple units are required for the U.F. membrane system to meet the greywater demand. This research presents the idea that for the US military, the ROWPU, after over 40 years of use, may not be the best option for non-potable water reuse in remote environments.

6.1 Research Questions

This research answers three questions. Listed below is each question with its respective answer.

1. How should the tradeoffs (cost, energy, and mobility) of each system be evaluated in order to properly obtain an ideal decision?

   Evaluating cost comes from the purchase price of the system. The energy efficiency is evaluated by the energy requirement and the water production of the unit. Finally, the mobility of the system is evaluated using the size and weight of the system or pallet size, as well as the permanence.
2. Which technologies are able to reuse greywater to lower the demand for fresh water on FOBs?

   Seven technologies were found in this research for greywater reuse. These seven technologies are ROWPU, UF membrane, Package System, MHMWTP, AdvanTex AX Greywater, MCW, Aerated cells systems.
3. Which technologies are best suited for use by the United States military?

   Of the technologies evaluated in this research, the AdvanTex AX greywater units and the UF membrane systems.

6.2 Limitations

A few factors limit this research. These factors include missing information, utilizing the unit cost used instead of full lifecycle analysis, and differing source water than initially intended for the systems. These limitations prevent a comprehensive analysis from being performed. Due to the review nature of this study, further research or experimentation may be required and impact the findings.

Some data for the technologies are unavailable through the literature review. Additional research would be needed on several selected technologies to complete a full analysis with the parameters set in this study. A few of the technologies are missing the price and the weight of the technology. This missing information directly impacts the analysis of the technologies. Supplementary information such as the system's longevity and the system's reliability would also affect the analysis but were not considered for this research. Additionally, evaluating a technology's environmental impact may have a further influence on the outcome of this research. However, the operational footprint of the unit is largely based on the energy source and energy demand of the system. As a result, environmental impact was excluded to avoid double counting with energy demands. A technology's ease of operation and maintainability would be an important aspect to evaluate in future iterations of the work. Due to the amount of time that the ROWPU has been utilized in the military, retraining troops to maintain and operate a new system would be a costly and time-consuming process. Furthermore, the ease of obtaining replacement parts for repair would be another aspect to evaluate for this research. Obtaining this information could influence the study's outcome, providing a better solution to the water reuse treatment options.

This research does not use a complete lifecycle assessment. By only utilizing the unit purchase price, we overlook the maintenance costs, reconstitution costs, and operational costs of each system. A full lifecycle assessment would utilize the maintenance cost and the cost to reconstitute or dispose of the system at the end of its service life. Full lifecycle assessments would account for the different technology lifespans and the reliability of the system.

The seven technologies evaluated in this research were developed with different water sources in mind. The Package System, Transportable UF Plant, MHMWTP, and the ROWPU were developed with ground or surface water as the intended water type. Utilizing these units for greywater may cause the system to require more maintenance than typical or cause the membranes in the system to foul quicker. Other unknown problems may present themselves upon actual experimentation and use. These outcomes are unknown due to the review nature of this research.

6.3 Recommendations for Future Research

There are several ways to expound on this research in the future. This research primarily focuses on the treatment of greywater for reuse in non-potable water situations. A recommendation for future research involves the potential to evaluate the reuse of all wastewater for austere locations. This potential research would expand on the potential water source and create a larger source of water. This research would have to investigate more rigid disinfection and treatment as there would be more contaminants in the water.

A second potential research area would be to use recycled water for more uses, including potable water uses. This research would involve looking at how to mitigate the "ick" factor. Because the water would be used for potable uses as well, it would be essential to be sure that it meets the potable water criteria, whereas, for the current research, the water may meet the potable water standards but does not need to.

A third option for future research would be to continue this research with actual experimentation, use of these technologies, and exploring further factors of impact. A practical application could identify the actual outcome and verify the tradeoffs of each technology, specifically the energy efficiency. Using these technologies in an experiment would also provide information not found through a literature review. This information could be how each technology would perform in the climate that the US military is operating in or in the environmental conditions of the theatre. This experimentation would provide information on the maintenance requirements and costs for each technology, as well as the requirements and costs for the reconstitution of the technology at the end of its lifecycle. In addition, utilizing an experimental approach could provide further tradeoffs such as environmental emissions, ease of operation and educational requirements for operation, reliability, and maintenance requirements such as obtaining replacement parts and repairing technologies.

Upon receiving complete data on these technologies, utility theory could help determine a best fit technology. This analysis would require all data for each technology, which would allow for utility curves to be developed, translating the tradeoffs into utiles or unit less equivalent values, and allowing the tradeoffs to be evaluated in equal units. From there, an equation could be developed for decision making. Using an equation similar to Equation 1, a decision maker would be able to obtain a numerical ranking system of the technologies presented in this research, as well as other technologies.

$$\boldsymbol{Total\ Utility} = (\boldsymbol{w_C C}) + (\boldsymbol{w_{EE} EE}) + (\boldsymbol{w_M M}) \tag{1}$$

Where *w* is *weight* as decided by the decision maker's placed importance, *C* is *cost*, *EE* is *energy efficiency*, and *M* is *mobility*. The objective of Equation 1 is to obtain a high total utility score. A high total utility score would mean the technology is a better fit for the individual situation. Utilizing utility theory would be beneficial for future research in this area.

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A secure water source is essential to the resiliency and readiness of military installations and contingency operation locations, especially those located in the dry climates the US military operates in today. There are multiple issues of concern when identifying water sources, such as security, cleanliness, accessibility, and sustainability. Water resources pose a potential vulnerability to mission readiness in a remote, agile environment, such as a forward operating base (FOB). Having a secure water resource helps facilitate mission readiness in the contingency environment, offering the opportunity to be more resilient and cost-effective.

Current water treatment technologies present the possibility to perform direct water reuse to mitigate water needs. This research evaluates seven technologies for the prospect of greywater (wastewater without human waste) reuse in agile environments. While there is no perfect solution when using water reuse technologies, considering the cost, energy efficiency, and mobility of each technology helps determine which technology is the best fit for each situation. This research finds the best overall solutions for a FOB of up to 500 troops are either the U.F. membrane or AdvanTex AX Greywater system. This ranking is based on the three evaluation criteria with the intent of mitigating the need for freshwater.

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