

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

WATER HOLES:

FILLING THE GAP FOR ANY CLIME AND PLACE

by

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DISCLAIMER

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ABSTRACT

The Marine Corps' strategic shift toward distributed operations necessitates modernizing sustainment models to accommodate small, highly mobile, and concealable forces. To address the change, Marine Corps engineers must integrate water harvesting technology with current equipment to provide potable water to distributed troops in austere environments. Bulk water production remains a critical capability that can only be abandoned partially to satisfy the broad range of force requirements and is a necessary measure for water security in austere locations under new paradigms. However, creating small quantities of water by extracting water from the air in places with limited infrastructure is more suitable for distributed operations as it avoids creating large footprints, decreases dependence on supply systems, promotes autonomy by eliminating the need to draw from a surface water source, and enables water production for mobile units that depend on rapid displacement for survival. Findings indicate that atmospheric water generation (AWG) is best served to supplement reverse osmosis (RO) water treatment systems and is effective when integrated with equipment to increase the agility of tactical units. Additionally, merging RO and AWG in single platforms represents an opportunity to incorporate sensor technologies for intelligent control of water resources in a distributed environment.

Introduction

The *2018 National Defense Strategy* outlined a bold shift from irregular war toward great power competition. It urged components to change institutional paradigms to modernize the means and ways they intend to fight and win. As a result, the Marine Corps adopted a new strategy to support the force better and reinvigorate commitment to Navy composite warfare through Expeditionary Advanced Based Operations (EABO). This new concept employs forces in a distributed fashion within the weapons engagement zone to circumvent anti-air access denial challenges.¹ Implementation issues include human sustainment, specifically water production, storage, and distribution. Therefore, Marine Corps engineers having a preponderance of responsibility for this task, must closely examine current water capabilities against the demands of a new component paradigm in the best bid for success in competition.

Following the Department of Defense's guidance, the Marine Corps subsequently released a series of overarching conceptual frameworks to distill clarity at a component scale, explaining force considerations in conducting warfare at and below the threshold of major combat operations and thereby inducing change from large force presentations to small and widely distributed combat teams. The Marine Corps released *Force Design 2030*, *Reconnaissance and Counter Reconnaissance*, *Tentative Manual for Expeditionary Base Operations*, and *Stand-In Forces* guidance to help synchronize this paradigm shift. Themes within these plans reflect a growing need for autonomy and mutual concern for sustainment. Therefore collectively, formal guidance acknowledges the disparity between current force structure, equipment, and desired capabilities; but is not prescriptive in describing logistical resilience and, in some cases, contradictory to signature management goals.

The issue of logistics in the context of change is particularly problematic for Marine Corps engineers as most supply and sustainment operations revolve around bulk liquid operations.² Engineers are charged to treat, store, and distribute water to convert bulk quantities for re-storage and issue to troops. This cycle assumes that a robust theater network is established and takes freedom of maneuver for granted, dismissing the risk-to-force concerns and opponent intelligence, reconnaissance, and surveillance capabilities. Engineer water treatment equipment is bulky and resource intensive. It demands an evaluation of the implications of the operational paradigm shift and re-conceptualization of tactical water support operations that must be captured in component frameworks.

To treat non-potable or ‘dirty’ water, most processes rely on chemical, evaporative, or pressure methods to convert it to potable or ‘clean’ water. Marine Corps engineers rely on pressure-type systems through a reverse osmosis process. Reverse osmosis is a tried-and-true process that removes contaminants but requires a surface water source, power, and additional service support structure that is incompatible with new Marine Corps concepts. To maximize effectiveness in a distributed environment, water support operations are best suited to be highly mobile, scalable, multi-capable, and available at the point of need.³ This will aid in minimizing the logistic burden of forces, improve signature management, and more fully promote expeditionary advanced-based operations.

Unfortunately, reverse osmosis systems are most efficient at treating water in bulk quantities under permanent or semi-permanent circumstances. These conditions must reflect the standards for employing distributed forces, as static operations undermine high mobility goals. Alternatives beyond reverse osmosis and a departure from bulk sustainment must be examined to improve Marine Corps autonomy. The need is critical considering the elevated risk troops endure

while conducting sustainment operations and the importance of maneuver in an all-domain battle spread across large swaths of air, land, and sea.

Scientific advancements in water harvesting technologies must be examined as a potential water sustainment solution to improve distributed forces' survivability, duration, and operational reach. With air-to-water technology, like atmospheric water generation, this study will evaluate the feasibility of using a tactically scaled, multi-purpose water purification unit to determine potential benefits in sustaining distributed forces. This study seeks to answer the research question: “How can Marine Corps engineers most effectively provide water to distributed forces in austere environments?” While other technologies, old and new, are broadly addressed, this research will limit its scope to atmospheric water generation. It will not evaluate water support alternatives that may also be available through contracting, interservice support, foraging, fabrication of fieldcraft devices, autonomous delivery systems, or other emerging technologies. Instead, this study focuses on technology that generates water through a mechanically assisted condensation process that does not require an open water source.

Evaluation for this report uses the problem/solution research framework method to study the suitability of water harvesting technology to determine how Marine Corps engineers can effectively provide water to distributed forces in austere environments. Four criteria will be used for quantitative assessment, sourcing technical data from primary sources and applying subject matter expert and peer-reviewed secondary sources for qualitative evaluations. Measures compare observable features of the Marine Corps' equipment against a commercial sample using physical attributes, stealth, the economy of scale, and equipment resource dependency as metrics. These compare characteristics of contemporary equipment sets against ruggedized atmospheric

water harvesting equipment to determine the suitability of water treatment equipment in austere distributed environments as defined in emerging operating concepts.

This study first provides background to small-scale water support challenges in the context of distributed operations and examines peer-reviewed research regarding the science behind commercial water harvesting technologies. A review of distributed operations, water purification equipment, and a description of water support operations will be provided for technical and tactical understanding to convey the significance of water harvesters. This report consolidates small-scale water planning considerations and incites evaluation of existing options by analyzing current military guidance and scientific reference material to address small water production gaps. The study then evaluates how engineers can prevent over-reliance on traditional bulk water operations by employing small-scale, essential life support options to improve the autonomy of troops using the criteria cited above.

This study assesses the feasibility of atmospheric water generation for providing distributed forces with a source of potable water. Explanation of novel Marine Corps concepts and existing and nascent water treatment technologies provide alternative considerations that may extend small-force self-sustainment's operational reach and duration. Using the problem/solution research framework, a discussion will follow the presentation of data to investigate the benefits and shortfalls of water harvesting technology. Finally, the results will conclude by comparing outcomes and recommendations for further or associated investigation.

Background

“The Marine Corps will be trained and equipped as a naval expeditionary force-in-readiness and prepared to operate inside actively contested maritime spaces in support of fleet operations. In crisis prevention and crisis response, the Fleet Marine Force – acts as an extension of the Fleet – will be first on the scene, first to help, first to contain a brewing crisis, and first to fight if required to do so.”

-Gen David H. Berger, 2019⁴

Force Transformation

The Marine Corps had a watershed year in 2019 when the Commandant of the Marine Corps, General David H. Berger, released the *38th Commandant's Planning Guidance* (CPG). Berger's CPG is widely regarded as a component-wide call for transformation that outlines the component's direction and demands significant changes in the manning, training, and equipping of Marine Corps forces to meet future needs. Specifically, his guidance addresses investing in naval integration and furthering the development of distributed operations warfighting concepts that “are designed to generate tactically disruptive, tactical stand-in engagements that confront aggressor naval forces with an array of low signature, affordable, and risk-worthy platforms, and payloads.”⁵ It regards the Marine Corps as ill-postured for naval operations and attributes failures in integrating experimental distributed operations concepts to institutional risk aversion and lack of doctrinal commitment.⁶

While Berger's CPG does not specify water support operations, the shift in strategic direction implies a new plan for sustainment and implied tasks for engineers to conduct self-assessment and find new ways and means to support radical change. Concepts and themes echo the concerns outlined in the *National Defense Strategy* released a year earlier that great power competition is afoot, suggesting widely dispersed squad-sized elements and even individuals with the proper support are crucial to imposing costs on distant opponents.⁷ In other words, the previous sustainment demand for units of employment shifted from consolidated company-sized

formations of 180 personnel to distributed squad-sized elements of 12.⁸ This implies that water equipment and personnel must mirror the shift from consolidated bulk water constructs to distributed small-scale employment modules.

Military pundits criticize CPG for demanding a radical change that creates unnecessary risk to the components' mission.⁹ General Berger explains that smaller units with increased distribution result in superior maneuver options and a reduced probability of detection for disrupting the enemy by creating a context of uncertainty.¹⁰ For answers, CPG looks at off-the-shelf technologies, naval integration, nascent autonomous logistic platforms, and sister-service investments to bridge sustainment gaps. Marine think tanks suggest subsidiary and infiltration logistics early to circumvent this problem. Subsidiary logistics attempts to use means like foraging and contracting to find localized solutions to problems but is challenged by highly circumstantial conditions and the availability of resources that cannot be wholly relied upon.¹¹ While logistic infiltration looks toward the novel application of technology to break or “infiltrate” logistic chains and develop innovative approaches to problems.

Atmospheric Water Harvesting

Atmospheric water harvesting is an example of one such solution. About 10% of all water is locked in atmospheric circulation due to the earth's hydrological cycle in the form of clouds, fog, and water vapor.¹² Water harvesting activities like collecting rain or fog harness natural phenomena such as dew formation or evaporation to collect water that is otherwise inaccessible for consumption.¹³ Tapping into earth's water cycle is appealing as air is an abundant renewable resource that promotes decentralized water production, thereby eliminating dependence on logistic chains for fresh water.¹⁴ It is especially appealing to the Marine Corps as

access to water anywhere may nullify site selection constraints and permit tactical units to move about the battlespace freely.

To scope this study, passive water harvesting methods that collect water without the aid of external energy will be discussed but not closely examined. This study focuses on active water collection processes of active cooling condensation used in Atmospheric Water Generators (AWGs). AWWs capitalize on water harvesting concepts by drawing water from the air, like a household dehumidifier or air conditioner. Generally, air-to-water machines use active cooling technologies that manipulate dew points to create water on the principle of water condensation.¹⁵ The key military advantage AWWs feature is the ability to produce water without an open water source that enables the ability to make water while on the move. A closer evaluation of Marine Corps concepts and equipment is warranted to better understand the potential of AWW on new operational paradigms.

Traditional Marine Corps Employment

Water is necessary for all human sustainment and is critical in determining any force's duration and combat readiness. As the nation's soldiers of the sea, the Marine Corps has a long history of exercising expeditionary operations. This requires deploying organic sustainment capabilities to be as independent as possible. Throughout the war on terror campaign, the Marine Corps routinely deployed 500 or more personnel in austere environments—places where little or no critical infrastructure like water treatment plants exist—resulting in a need for bulk water. During the campaign, engineers would establish centralized water purification sites on bases and outposts near water holes like wells or river shores for drinking and personal hygiene to support battalion operations.

Engineers are often the first to satisfy water requirements with bulk water treatment capabilities for combat operations and crisis response, equipment maintenance, emergency services, and nation-building activities.¹⁶ Planners generate a water demand based on consumption estimates ranging from two gallons per person in cold climates to six gallons in arid desert climates. They must achieve potability standards to be safely consumed.¹⁷ Ranges vary by equipment availability, storage capacity, distribution methods, type of water to be treated, and various conditions. Calculating water demand is also complicated by the operational circumstance, which can elevate a demand as high as 18 gallons of water per day/ person.¹⁸ The chart below reflects the typical water range per person required by climate to understand the water demand better.

COLD CLIMATE	2 gal (7.57 liter)	day/per person
HOT CLIMATE	3 – 4 gal (11.35 - 15.14 liter)	day/per person
ARID CLIMATE	3 – 6 gal (11.35 - 22.71 liter)	day/per person
TEMPERATE CLIMATE	2.9 – 4 gal (11 – 15 liter)	day/per person
COMBAT READY	2.12 gal (8 liter)	day/per person
SURVIVAL	.5 gal (2.27 liter)	day/per person

Table 1. Water Requirement by Climate. *Adapted from* Marine Corps Reference Publication (MCRP) 3-40D.14, *Water Support Operations*, table 3-1; and author's collation of published data.

Driving water requirements are the factors of unit size and duration. The basic unit of action for conventional operations is the infantry rifle company which has about 180 personnel. The duration of employment varies by mission, but doctrinal sustainment calls for fifteen days of supply.¹⁹ Therefore, bulk water operations are suitable for conventional operations, and considering water weighs about 8.3 pounds per gallon, it is necessary to establish resupply hubs to lessen combat loads. Bulk water operations are also required as daily water sustainment accounts for 30-40% of troop sustainment, and a 6% water deficiency can result in complete ineffectiveness.²⁰

Transformation Impacts on Water Demand

However, the Marine Corps expanded operational paradigms from large force presentations toward a strategy that calls for light, very small, disaggregated, and concealable forces of less than 20 personnel in pursuit of Distributed Maritime Operations (DMO).²¹ Extensive rear-to-front water management highlights the incompatibility with new strategies, which require teams as small as three or four persons to operate clandestinely in the fight over intelligence in a weapons engagement zone.²² In a manner of speaking, the degree of force distribution directly correlates to the duration of self-sustainment: the more forces are dispersed, the more self-sustaining they ought to be, which implies producing water at the point-of-need and at a smaller scale can provide increased flexibility, commander decision space, and options.

Climate	Conventional Operations		Distributed Operations	
Note: Gallons Per Person Per day (GPD)	Rifle Company (Light) 180 Persons	Battalion Landing Team (Heavy) 1,200 Persons	Distributed Force (Light) 12 Persons	Distributed Force (Heavy) 20 Persons
COLD, 2 GPD	360	2,400	24	40
HOT, 3-4 GPD	540 – 720	3,600 – 4,800	36-48	60-80
ARID, 3-6 GPD	540 – 1,080	3,600-7,200	36-72	60-120
TEMPERATE, 2.9-4 GPD	522 – 720	3,480-4,800	35-48	58-80
COMBAT READY 2.12 GPD	382	2,544	25.44	42.4
Extreme or Special Circumstance				
SURVIVAL .5 Gal GPD	90	600	6	10
*Full range of required activities, >15 GPD	2,700	18,000	180	300

Table 2. Demand Comparison Chart Between Conventional and Distributed Operations. This chart is the author's collation of data *Adapted from* MCRP 3-40D.14, *Water Support Operations*, table 3-1.

Table 2 demonstrates the daily water demand calculations between conventional and distributed force employment models. Immediately, scalability is highlighted as the core problem since equipment intended for bulk water operations produces too much water and comes with a

significant logistics tail. Further scalability issues emerge with water storage and distribution, considering battalion landing teams secure fifteen days of self-sustainment, resulting in a more significant difference between traditional and new employment models. Such disparity is exacerbated by access and distance between service provider hubs and troops.²³ This indicates that water sustainment practices need an adequate solution for emerging service needs. In this sense, the Marine Corps has elevated the urgency for a component overhaul to include water sustainment of troops.

Scalability challenges are familiar to other services. The Air Force has also adopted a distributed Agile Combat Employment (ACE) strategy that features small, flexible, and rapidly deployable forces to gain and maintain access in remote areas.²⁴ Air Force concepts feature the use of temporary drop-in bases and fighter forward arming and refueling points that are geographically dispersed, which is much in line with Marine Corps DMO.²⁵ It has inspired Air Force investments in multi-purpose technologies that incorporate atmospheric water generation as a flexible means to sustain small groups of people abroad. Trials conducted in June and July 2022 by the 52nd Civil Engineer Squadron in Otwock, Poland, demonstrated that a group of three to five personnel equipped with a militarized water and power harvester and two pick-up trucks could sustain basic operations with water and power for 13 days at about a gallon of fuel a day.²⁶ This alternative approach to sustainment serves as an example of how the Marine Corps may improve its approach to small-scale operations and demonstrates the potential benefits of water harvesting as a feasible approach.

Distributed Maritime Operations, Expeditionary Advanced Bases, and Stand-In Forces

“Distributed Operations describes an operating approach that will create an advantage over an adversary through the deliberate use of separation and coordinated, interdependent, tactical actions enabled by increased access to functional support, as well as by enhanced combat capabilities at the small-unit level.”

A Concept for Distributed Operations, 2005
Gen Michael W. Hagee²⁷

Following the CPG, three important Navy-Marine concepts were accelerated to clarify the role and function of the Marine Corps. The first is Distributed Maritime Operations (DMO), articulating how Marine Forces are distributed composite elements in Naval formations to codify Marine Title 10 responsibilities.²⁸ DMO is a fundamental challenge to water support as centralized water production focuses on a hub-and-spoke principle that poorly aligns with dynamic, disaggregated conditions for operations in a non-contiguous battlespace. This indicates that water treatment practices must modify decentralized point-of-need production, storage, and water distribution approaches for DMO.

The second concept of Expeditionary Advance Based Operations (EABO) addresses the role of Marine forces in a weapons engagement zone.²⁹ Marine Corps tentative EABO doctrine advises sustainment operations at forward support base locations as a required activity that demand higher levels of concealment, diversified planning, and efforts to reduce the burdens on logistics chains, including water.³⁰ As the Marine Corps has been resigned to base camp operations to support sustained land operations and amphibious landings, the tables of equipment, training, and personnel are accustomed to forward deployed but static operations near a surface water source. As a result, water equipment needs to be better suited to fulfill EABO water operations because equipment depends on an available water source, centralized logistics channels, and technological superiority.³¹ Said differently, EABO attributes of “mobile, low-

signature, persistent, and relatively easy to maintain and sustain”³² necessitate highly mobile water sustainment capabilities to achieve economy-of-force and avoid adversary observation.

The third concept of Stand-in Forces (SIF) is closely related to DMO and EABO but drives “[operations] across the competition continuum within a contested area as the leading edge of a maritime defense-in-depth,”³³ which elevates the significance of signature management. SIF relies on reconnaissance and counter-reconnaissance proficiencies to fuse information with capabilities that can close kill webs in enemy weapons engagement zones. More plainly, very small and geographically disparate sea or shore-based troops gain and maintain custody of potential targets with equipment to see, orient, and, if necessary, attack first.³⁴ However, the contending force must avoid being found to secure the element of surprise and find a target first. Therefore, stealth and speed are essential to a Marine force’s ability to sustain and operate and must be accounted for during equipment selection processes. Since water equipment requires power, a water source, and a sizeable footprint, retaining concealment can be difficult and reframes engineer considerations on how to satisfy operational requirements. Static water treatment contradicts these attributes and suggests that the ability to create water while mobile can be advantageous in a SIF situation.

It is important to note that adaptive reconstruction of the Marine Corps through DMO, EABO, and SIF is intended to supplement traditional roles as an expeditionary force in readiness. These concepts do not relieve the Marine Corps from conventional force employment missions that require bulk water operations. The Marine Corps retains Title 10 responsibilities to man, train, and equip forces in response to global disaster, disruption, or disputes that require bulk water operations for humanitarian aid, disaster relief, and amphibious assault.³⁵ These concepts are an added capability that expands the scale of an already robust multi-mission identity,

whereby EABO and SIF are complementary capabilities. Therefore, water support operations must be equally versatile to match engineer capability and capacity regardless of the assigned task. This further implies that retention of current capabilities is necessary, albeit expanded strategies demand new equipment or changes to water support constructs.

In early 2022, the Marine Corps experimented with these new concepts by forming Task Force 61/2 that positioned task elements and even individuals, dynamically challenging water sustainment constructs throughout the Mediterranean and European continent.³⁶ While Task Force 61/2 was experimental, it became clear that traditional sustainment methods were incompatible with the SIF model. It demonstrates that a permanent change in strategy will require a more transportable and self-contained water production capability to support small, widely distributed units in isolated areas.³⁷ Troops were absent water technicians and small-scale water production systems and instead resorted to channels of interservice support, leveraging partner resources, purchasing packaged water, and traditional base operation support integration to achieve ends.³⁸ While these methods demonstrate merit in resourcefulness and interoperability, sourcing water sustainment could reveal troop locations and place trust in tethered logistics while assuming the availability of commercial resources and infrastructure—neither guaranteed in the operating environment.

Distributed operations pundit retorts criticize that too much change creates logistic uncertainty to reliably performing in the operating environment.³⁹ Others may claim that reliance on black-bottom shipping, naval support, and nascent autonomous logistic platforms is far from reality.⁴⁰ However, EABO and SIF acknowledge the impacts of modern technological growth and the changed operating environment.⁴¹ Such changes have opened doors to novel threats that take advantage of operating force signatures, impede freedom of action, and challenge the ability

to project power at will. For this reason, water systems have undergone considerable scrutiny and forced renewed component-wide efforts to encourage experimentation.

Atmospheric Water Generation. While equipment has become lighter and more efficient, the paradigm shift highlights a gap between engineering strategies and equipment to find suitable and straightforward solutions to the complex problem of distributed force sustainment. Said differently, emerging concepts stress bulk water operations' ability to provide water to small, distributed units without revealing locations and forfeiting autonomy where it is most needed. Engineers have pursued Atmospheric Water Generators (AWGs) throughout the Marine Corps to avoid logistic chain dependency and simplify water operations for small unit needs.⁴² AWGs are attractive as they combine water production and storage capabilities at a much smaller scale than traditional systems.



Figure 1. Mounted Atmospheric Water Generator. *Photo credit, Corporal Patrick King.* (Adapted from Kelsey D. Atherton, “Make Drinking Water from Thin Air,” *Popular Science*, 29 November 2022, <https://www.popsci.com/technology/marine-corps-atmospheric-portable-water-sustainment-unit/>.)

Field testing in the Marine Corps continues with systems like the ones pictured above to assess beneficial features like low-maintenance requirements, portability, compatibility with multiple power sources, and minimal training requirements.⁴³ Depending on the system, AWGs

are generally capable of generating a gallon of water per hour and feature an internal secondary containment capacity in the tens-of-gallon range. Internal storage capabilities are a vital consideration as it avoids stationary setup of peripheral systems, contributing to making SIF less predictable and more easily concealed. The compact size makes systems portable on light off-road vehicles and can be handled by one or two people. Additionally, AWGs are often paired with solar power energy sources, making them an attractive technology for new employment models.⁴⁴ Overall, AWGs lessen liquid transportation, storage, and distribution requirements and are seemingly an ideal solution for distributed operations.

However, after-action feedback reports often state that AWG production yields need to be increased in low-temperature or low-relative humidity environments.⁴⁵ High-humidity environments tend to have available open water sources, which lessens the need for sourcing water from the atmosphere if shorter, and historically more reliable means for water treatment are available.⁴⁶ Also, despite design improvements, many AWG systems need to be smaller and lighter to support stand-in force mobility needs, indicating they may be more appropriate for stationary operations. Such limitations suggest that AWGs lack the flexibility to serve the global response force's needs and are best suited in tropical environments. To address this restraint, the scientific and commercial communities have invested in studying sorbent materials, often called Metal-Organic Frameworks (MOFs).

Unlike AWGs that work on condensation principles, MOFs are absorbent-adsorbent materials that first fill up with water at a molecular level which can be later extracted.⁴⁷ They are called MOFs because it combines organic substances and special metals that attract and resist water to increase production.⁴⁸ While there are many types, recent experiments indicate that a gallon of water can be made in desert environments with less than 8.5 pounds of sorbent.⁴⁹ This

implies that integrating MOFs in military water harvesters can avoid production issues in low-humidity environments for more universal applications.

The Defense Advanced Research Projects Agency (DARPA) has established a formal Atmospheric Water Extraction (AWE) program, which is currently underway to closely evaluate the potential of MOFs for military application.⁵⁰ The program is intended to integrate sorbent technologies into systems that can be applied to small units and even individuals in low-humidity environments, which resolves a preponderance of logistic and sustainment issues concerning water. While MOFs are attractive, the technology is relatively nascent and raises other issues with power requirements, material life cycles, and water quality.⁵¹ As a result, it may be assumed that a military MOF water production module may be forthcoming but not immediately available. For this reason, this study will assess atmospheric generators to more closely evaluate the tradeoffs of AWGs in comparison with traditional equipment and not closely investigate MOF technology.

Gyrene Mangrove Atmospheric Water Generator (AWG). In heeding the Marine Corps Commandants' planning guidance, Marines can look at the Air Force, which is also changing in support of distributed concepts. The Air Force assumed a similar strategy before the Marine Corps through the Agile Combat Element (ACE). This concept disperses positions throughout an area of operation. It seeks to employ rapid expeditionary airfields to identical attributes of Marine distributed forces as highly mobile, very small, and easy-to-sustain standards. In an Air Force component study by the RAND corporation, challenges associated with water sustainment were identified as critical to making the ACE concept work.⁵² As a result, the Air Force committed resources to identify innovative solutions to reduce logistic water requirements and

improve sustainment options at scale. Specifically, an annual competition called “Spark Tank” was established to resource creative ideas and evaluate advanced research concepts for application toward ACE endeavors.⁵³



Figure 2. Gyrene Engineering Management's Mangrove. An expeditionary, modular, water and energy harvesting system designed for fire-team to platoon-sized operations. *Note: Illustrations from left to right, P-1A stand-alone, P-3A skid-mounted, and P-3B vehicle-integrated systems.*

Photos provided courtesy of Gyrene Engineering Management owner Michael J. Smith.

Project ARC water was awarded first-place recipient in 2022 for proposing a green-energy system that combines energy and water harvesting technology with reverse osmosis and ultra-filtration technology to reduce logistic air resupply demands. The proposal incorporated a commercial, multi-source water treatment system called “Mangrove,” pictured above, because of its ability to purify salt, brackish, and freshwater just like the marsh plant. Mangrove is an all-in-one system that infiltrates logistic chains and eliminates cargo requirements for packaged water or water support equipment. The system is made by Gyrene, which specializes in military-grade technology. Mangrove is designed as a ruggedized, self-contained water and power harvesting system that can either stand alone or be integrated into vehicles.⁵⁴ As global mobility is among Air Force core missions, available cargo space dictates what is operationally feasible, and the Mangrove provides self-sustaining power and water at quantities suitable for ACE operations.⁵⁵

To the Air Force, Mangrove represents an alternative solution to support the establishment of rapid forward arming and refueling sites, expeditionary airfields, and support

warfighters in distributed environments. Despite differences in application intent, the Mangrove represents a feasible alternative or addition to existing Marine Corps systems because of its reduced size, simplicity, and versatility to support many circumstances. Notably, the Mangrove system features AWG capabilities to harvest water at a minimum of 28 gallons per day at 80 degrees Fahrenheit and 60 percent relative humidity.⁵⁶ It differs from other AWGs as it consolidates water storage and treatment with power harvesting capabilities on a single mobile platform, taking up less than 3.8 cubic feet of space.⁵⁷

Mangrove is unique as it includes a miniaturized reverse osmosis (RO) water production module and integrates a 20-gallon water storage tank with dispensing capabilities at a smaller scale than traditional water treatment systems.⁵⁸ These features highlight benefits as a simplified sustainment solution capable of expanding water production if demand increases or providing RO options in low-temperature or low-humidity environments where AWG may be insufficient. Further, the configuration can be modified to produce water from the air while moving, a military advantage to forces that depend on mobility for survival in a weapons engagement zone. While systems can be customized to integrate with any mobile platform, it weighs over 250 pounds, excluding foot mobile applications.⁵⁹ The Gyrene Mangrove is this study's primary point of comparison as an alternative water solution to support distributed forces.

Implications and Key Issues

Suffice it to say, Marine Corps enterprise concepts can learn from Air Force Agile Combat Employment (ACE) concepts to inform the Corps' approach to traditional water support operations by emphasizing engineering activities closer to the logistical edge. It highlights tradeoffs between employment methods that exchange size, power, and resource accessibility with values like stealth, speed, agility, and economy of scale that seek to "reduce the burden on

distribution networks.”⁶⁰ This implies water systems must be more self-supporting, lighter, and less logistically burdensome to adopt an extremely mobile, scalable approach to offset traditional overreliance on logistic chains. While force transformation encourages the development of capabilities to decentralize water support operations, new concepts must now acknowledge that equipment must be globally distributed, supportive of low-signature management, suitable for all climates, simple to operate, and capable of purifying water from all sources.

Complexity. As engineer water support has been resigned to centralized base camp operations in support of sustained land operations and amphibious landings, the concepts of distributed maritime operations (DMO), expeditionary advanced base operations (EABO), and stand-in forces (SIF) add levels of complexity to water support planning that may make forecasting demands extremely difficult.⁶¹ Opponents and threats are not restrained by geographic command features and can complicate circumstances that undermine engineers’ abilities to plan with very high confidence. As battlespace conditions and operations drive water support, it may be exponentially more challenging to identify solutions and manage capabilities that new distributed concepts require. Therefore, decentralized, point-of-need water production is worthwhile but may not be reasonably or efficiently achieved with current capabilities.

Studies suggest diversifying water solutions may improve water resilience and can be linked to Marine future operating concepts to make forces less observable and unpredictable. To address the added complexity that emerging concepts inject into water support operations, the effects can be lessened by diversifying equipment sets and operational approaches. In response to the *2021 United Nations World Water Development Report*, the Beijing Municipal Commission of Education funded one such study to examine water resilience in the wake of extreme weather

events and evaluated water harvesting among potential solutions.⁶² The review team characterizes a variety of water sources and treatments. It posits that atmospheric water generation can offset costs and provide viable means to produce potable water as an alternative to conventional means of delivering water with more significant environmental and price efficiency.⁶³

While the study focused on sustaining large urban populations and communities with poor infrastructure, the review team's emphasis rested on creating water independent of surface water features with water harvesting technologies and considered variables such as sunlight, relative humidity, and regional conditions to present the reader with associated air-to-water technology tradeoffs. One critical conclusion was the emphasis on diversifying water sources to build resiliency. In other words, reliance on a sole solution for water security is a fickle prospect. Considering the exponential combination of conditions brought about by new strategies and an ever-changing operational domain, this is a crucial observation that Marine Corps engineers should expand water treatment beyond reverse osmosis equipment but not abandon current practices. A single technology or equipment solution is seldom appropriate for all situations. Developing a layered logistical strategy with more versatile and multi-capable equipment to supply water to troops is a possible winning strategy to overcome the challenges of diverse environments.⁶⁴

Additionally, water support is based on wide-ranging conditions implying significant effort must be put into engineer reconnaissance and planning. Although Marine Corps think tanks recommend subsidiary and logistic infiltration approaches, they require the ability to assess and deconflict factors beyond human capacity to calculate. While not addressed in detail, research suggests that artificial intelligence, computer simulations, and modeling may provide

the means to forecast demands, define troop and equipment status, and facilitate predictive logistics.⁶⁵ Computer technologies may be applied to various water support factors, from estimating climate impacts, predicting maintenance, managing equipment, or surveying local infrastructure and resources.

In the research article, *Assessing Uncertainty and Risk in an Expeditionary Military Logistics Network*, Brandon McConnel et al. address unraveling logistic complexity and forecasting supply and demand problems through simulation and modeling logistic networks.⁶⁶ The research aimed to demystify large complex logistic webs to find efficiencies. McConnel's analysis suggests that simulation support can interpret complex factors to enhance planning for water sustainment at any scale. McConnel's study implies that Marine Corps engineers can leverage computer modeling programs to rapidly plan for water support operations—even before deploying troops. The notion may be connected to water treatment analysis and de-conflicting demands based on urgency or efficiency to avoid failures and clarify risk to force, like standard energy grid or water management practices.

Computer software and applications can undoubtedly remove human error and facilitate advanced calculations that better predict water demand. Incorporating artificial intelligence to engineer reconnaissance and resource management can remove complexity, provide decision space, and increase time for other operations. Simulations may even conduct variable analyses of troop hydration needs according to levels of human activity for exact water estimates that may reduce waste and promote field conservation techniques.⁶⁷ This implies that linking diversified water solutions with computer programing and software applications can modernize operational constructs to simplify overwhelming complexity.

Geographic Disparity. Shortly before the Commandant of the Marine Corps' pivotal announcement that Marines would return to their Title 10 responsibilities but in a new way, the Navy broadcasted its own renewed overarching warfighting concept in *A Design for Maintaining Maritime Security 2.0*.⁶⁸ To this effect, the Navy defined the term “distributed maritime operations” after evaluating the benefits of distributing lethality to mean “...forces, platforms or capabilities intentionally spread over an area to accomplish some designated military task.”⁶⁹ Falling under the Department of the Navy, the Marine Corps places its bid for success following the Navy’s commitment to spreading forces throughout the maritime domain and across geographic boundaries to cast a sensor-to-shooter web and close the kill chain. Being distributed then means SIF and EABO Marines will find themselves more often under the operational control of a single geographic commander but tactically employed for missions across multiple boundaries.⁷⁰

This raises the issue of different environments as distributed operations entail cross-boundary activities. Not all climates are the same, and the availability of logistic services differs by mission, objective, and host nation resource availability. For example, extreme differences in environmental circumstances exist between littoral island chains in the Pacific and those in the European high-north region. Regional environments also differ in infrastructure and geography, which prevent the feasibility of a single system or approach to operations. Further, as MAGTF or sea-based platforms provide support, sustainment becomes a matter of regional access, speed, equipment or platform availability, and organization—all significant factors impacting water support operations.

Current water treatment equipment requires an open water source to produce potable water, which dictates that the areas troops intend to occupy must also have access to a surface

water source. While operating in littoral regions as an amphibious force implies access to raw water sources should not be problematic, the limitation can be informative to opponents' narrowing the location of troops, avoiding detection. Additionally, sourcing water from open sources results in static operations that increase the probability of detection or necessitate hose-reel systems which impose equipment costs that light, highly mobile units cannot afford. Distributed operations still require tactical water sustainment options conducive to maneuver while taxing the warfighter and support structure less.

Scale. The change in the size of a unit of employment is critical to this study. The below table represents a modified water estimation chart assuming distributed operations factors. While demand may increase to 1,200 gallons for four days, the average demand ranges between 93 and 227 gallons for a distributed task element to operate. This translates to an unsuitable 772 to 1,885 pounds of water for a single SIF short-duration mission, precluding man-carry options.⁷¹

*Climate	Distributed Operations		**Demand for Four-days
*Values in gallons per day	Distributed Force (Light) 12 Persons	Distributed Force (Heavy) 20 Persons	**Note, minimal period assumed for task elements in the conduct of EABO.
COLD	24	40	96-160
HOT	36-48	60-80	144-192
ARID	36-72	60-120	144-480
TEMPERATE	35-48	58-80	140-320
COMBAT READY	25.44	42.4	101.76-169.6
SURVIVAL	6	10	24-40
*Full range of activities	180	300	720-1,200
* Demand may increase for hygiene, cooking, and medical needs to >15 gallons/day. ** Engineer reconnaissance estimates provide refined demand. Although enduring self-sustainment is most desired, this chart assumes four days with complete autonomy to conduct tactical tasks.			

Table 3. Distributed Operations Minimum Demand Estimate. Chart composed by the author from collated published data adapted from MCRP 3-40D.14, *Water Operations*, fig. 3-1.

Atmospheric water generation (AWG) offers promise for the Marine Corps to create drinkable water from active cooling technologies in quantities in tens of gallons which is more suitable and accessible for smaller groups of people.⁷² While the Marine Corps and Department

of Defense continue to explore the application of AWG, the issue of relative humidity must be addressed. AWG points to unreliability due to efficiencies dictated by the environment,⁷³ which is a challenge and a key reason why AWG or traditional water treatment alone is a wrong approach. As AWG works best in temperate climates with high humidity, it is difficult to predict exact regional conditions, which are also subject to seasonal change, elevation, and weather. This indicates that the use of AWG should be accompanied by enhanced engineer reconnaissance activities that elevate the importance of weather and conditions. Moreover, it is impossible to predict the location where troops will be called to action, making a commitment to AWG a circumspect investment. Such critical shortfalls validate common expert advice that providing water resilience to austere populations is most secure when using reverse osmosis systems and open lines of communication ties to infrastructure.⁷⁴

However, the commercial and scientific community have sought water harvesting technologies to identify clean, accessible, low-cost means of delivering water in places lacking infrastructure.⁷⁵ Though studies demonstrate it is feasible to extract water from the air in climates with relative humidity values below 30 percent, it remains a new understanding of how water sustainment operations in distributed environments must look beyond conventional military practices.⁷⁶ This suggests that a continuous review of commercial, experimental, and practical water harvesting technologies considering austere conditions is necessary. The dependency on environmental conditions indicates that military AWGs should incorporate onboard sensors to help synthesize battlespace awareness and inform predictive logistic models.

While this study does not address the benefits of incorporating sensors, it is important to note the potential benefits sensors can add to domain and asset management. Distributed equipment that can relay maintenance conditions, environmental factors, and run water

production calculations lessens the possibility of human error and increases awareness for operations and water sustainment. Sensors can also relay water quality analysis to reach-back locations that would remove requirements to have water or health technicians on site and improve overall autonomy.⁷⁷ The broad indication is that merging technologies and capabilities may require special considerations as engineers develop water support approaches to EABO and SIF concepts.⁷⁸

At a minimum, AWG may serve as a complementary capability for improving water resilience.⁷⁹ As air is found everywhere, AWG technology is used commercially in off-grid and austere locations to eliminate the need for supply distribution systems. In many circumstances, it may offset demand requirements. Regardless of identifying the right technology or process, failing to fill this gap will resign Marines to contract water sustainment and rely on supply chains for provisions that undermine the tactics General Berger envisions, ultimately denying the potential to exploit technologies for in-land operations, humanitarian aid, or missions other than war.

Marine Corps Engineers

A review of current practices is needed to understand the benefits and disadvantages of adding technologies. The immediate impact water has on operations qualifies water to support the most significant operations engineers to provide as it drives operational reach, extends the duration of sustainment, and enables freedom of action for deployed troops.⁸⁰ Marines generally rely on packaged (i.e., bottled) and bulk water (i.e., volumes more than 400 gallons) support from contracted or naval vessel services during an initial landing at an objective site until engineers establish a water point using unit-owned reverse-osmosis (RO) treatment systems. The Marine Corps has relied on reverse osmosis water purification technology for nearly half a

century to produce consumable water for military sustainment. While large and maintenance intensive, most reverse osmosis systems are reliable and capable of producing large quantities of potable water from salt, brackish, and freshwater sources to be stored, transported, and delivered to thirsty troops.

RO became the system of choice over previous filtration systems because of its superior ability to remove salt and harmful microscopic organisms, viruses, chemicals, and non-organic materials. Water is pre-treated with chemicals and filtered to reduce turbidity (suspended matter) before entering a series of special membranes that remove the remaining total dissolved solids to create product water. This process is complete after adding additional chemicals to ensure disinfection before final storage and subsequent distribution. The process is necessary as the system is designed to meet safety standards, as the presence of chemicals or biological pathogens could have catastrophic results.⁸¹

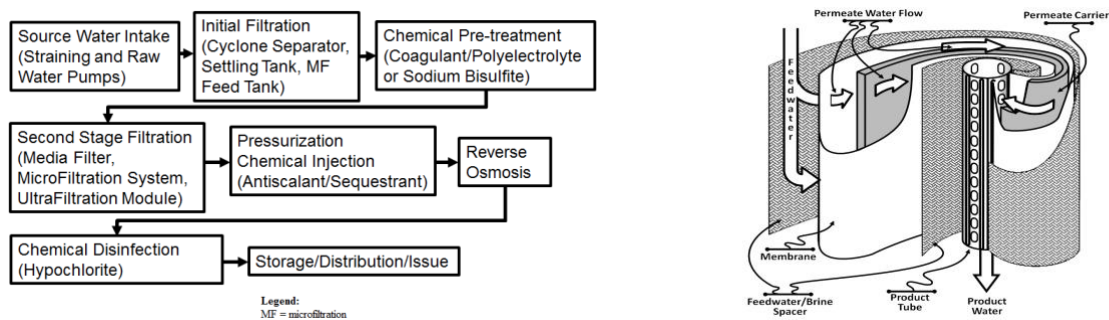


Figure 3. (Left to right) Water treatment process and RO membrane. Illustrations reprinted from MCRP 3-40D.14, *Water Support Operations*, figures E-1 and E-4.

Marine engineers responsible for water treatment are called water technicians and are spread throughout the force in Marine Logistics Groups, Marine Wing Support Squadrons, and embedded in Marine Expeditionary Units. As the Marine Corps operates along an expeditionary force in readiness philosophy, they employ a Marine Air Ground Task Force (MAGTF) model

that combines command, air, ground, and logistics elements. It is important to note that water technicians typically have a supporting role in the logistic combat element to combat arms units in Fleet Marine Force and are not necessarily organic to maneuver units.⁸² In other words, engineer types attached to maneuver forces vary by unit, location, mission, and circumstance because employment models rely on a modular organizational structure that results in a habitual but irregular relationship between infantry fighting units and water technicians.

Water technicians and engineer specialists service the equipment and aid in planning sustainment operations to support the greater force. Base camp planning is a significant function as it forecasts water needed for consumption and impacts equipment deployment lists, operational plans and schedules, and the disposition of equipment and personnel that can heavily influence mobility and logistic plans. Therefore, balancing requirements can be challenging because associated missions like preventative medicine, area security, transportation, storage, and maintenance must also be considered. Beyond water treatment, engineers provide service and support functions, including testing, storing, distributing, issuing, and safeguarding potable water products. Engineers achieve such service and support by using an extensive array of equipment ranging from specialized water containers to complicated systems of pumps and hoses.

UNIT	Daily Production Rate (gallons)	Storage (gallons)
CLB, MLG	78,000	96,000
CLB, MEU	78,000	45,600
ESB, MLG	840,000	746,000
MWSS, MAG	153,000	300,000
CLB = combat logistics battalion ESB = engineer support battalion MAG = Marine aircraft group		MEU = Marine expeditionary unit MLG = Marine logistics group MWSS = Marine wing support squadron

Table 4. Marine Corps Water Production and Storage Capacity. *Reprinted from MCRP 3-40D.14, Water Support Operations*, (2015), table 2-3.

Complicated planning, site preparation, maintenance, sustainment, and operations often dictate how water support is provided. For this reason, sites are selected based on operations and are gradually improved over time. Water treatment is completed in bulk quantities at anywhere between 125 and 1,500 gallons per hour. It is then stored in large vats and distributed by trucks, hardened storage tanks, or trailers for further storage and distribution until it reaches the consumer. The abovementioned hub-and-spoke process requires heavy equipment, personnel, and a predictable supply chain to keep operations running smoothly and function as a central water distribution point until occupational forces assume area responsibilities or alternate water solutions are found. The above chart shows the water production and storage needed to meet conventional needs. It demonstrates how current capacities are well suited for bulk operations but excessive for disaggregated small-unit operations.

While initially burdensome, the process has been an effective means of sustainment for forces greater than 150 personnel or other missions requiring large quantities of water like humanitarian assistance, base operational support, chemical decontamination, or construction operations. The equipment, operators, and support concepts work well for component expeditionary strategies that require bulk production and assume access to a support network and availability of a water source. The modular and expeditionary nature of Marine formations lends itself to expand, contract, and project forces with relative ease as engineers and logistic entities help make connections in the physical air-land-sea triad. The scalability of water support systems is thus designed to support all echelons of the MAGTF from company to regimental-sized units with considerable reliability, but unfortunately, not intended to support individual or squad-sized elements.

Current State of Water Support Technology

A review of the current and emerging Marine Corps water production inventory is essential to this study to provide a baseline for comparison with an atmospheric water generator. Additionally, recent Marine Corps investments in a family of expeditionary water systems demonstrate component cognizance of a capability gap and must be considered. The below table reflects critical attributes of the Marine Corps family of expeditionary water systems, followed by a discussion of crucial equipment. The chart calls out the need for a common power source among all systems that decreases the adaptability and flexibility of equipment serving under various circumstances. It also highlights how personnel taxes can further limit the feasibility of operations. The production rate emphasizes the unsuitability of scale, while the storage column calls out gaps in scalable water storage solutions. Each system is discussed in detail below.

System	Water Intake Source	Power Source	Manpower	Rate (gallons)	Storage (gallons)	Remarks
TWPS	Fresh Brackish Salt	Electric (Increased fuel demand)	>2 persons -special skills	36,000/day (F) 28,000/day (S)	6,000	-Resource Intensive -Peripheral equipment -Major Combat operations
LWPS	Fresh Brackish Salt	Pressure Pump (Increased fuel demand)	2 persons -special skills	*3,000/day (F) *1,800/day (S)	3,000 or 1,000 bladders	-Modular Components -Major Combat Operations
PWPS	Fresh Brackish Salt	Electric (multi- source)	1 person -low skill	528/day (F) 432/day (S)	-immediate consumption -individual containment	-Two-man lift -Platoon to Company Ops
SWPS	Fresh Brackish	Manual (pneumatic)	1 person -no skill	On demand 0.625gal /min (F) 0.47 gal/min (B)	-immediate consumption -individual containment	Currently in Field Testing
TWPS – Tactical Water Purification System LWPS – Lightweight Water Purification System PWPS – Platoon Water Purification System SWPS – Squad Water Purification System			F – Fresh B - Brackish S - Salt	*Comments: LWPS has multiple configurations, High 400 (S)–800 (F) gallons per hour (GPH) Medium 135 (S)—235 (F) GPH Small 75 (S) –125 (F) GPH		

Table 5. Marine Corps Family of Expeditionary Water Systems Chart. Author's collated data *adapted from* MCRP 3-40D.14, *Water Support Operations*, and Marine Corps Systems Command, Expeditionary Water Systems Project Office, in discussion with the author, 30 January 2023.

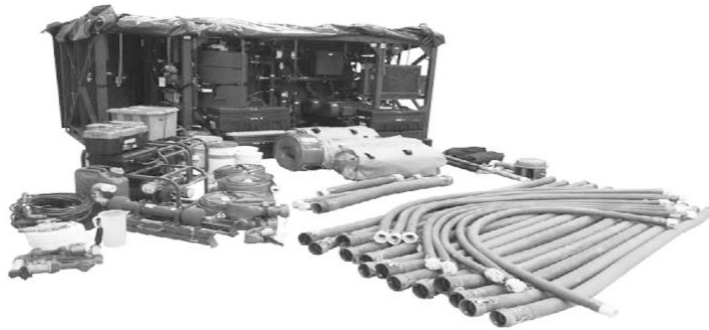


Figure 4. Tactical Water Purification System. *Reprinted from MCRP 3-40D.14, Water Support Operations, Fig. 4-10.*

Tactical Water Purification System (TWPS). TWPS is the largest Marine Corps water treatment system effective for large hub-and-spoke style sustainment and can be transported on large aircraft and trucks, as depicted above. Setup requires heavy equipment, a static site, an open water source, and power, supply, and maintenance support. Distribution is achieved in bulk by transferring product water to secondary containment bladders, water trucks, or hardened container systems.⁸³ A water distribution system can be attached to pump water over long distances but must be protected by a security detail to prevent compromising product water. Due to maintenance and operational complexity, the system's excessive size can be problematic for expeditionary operations. Therefore, the system is most suitable for major combat operations. The Marine Corps seeks to retire the equipment soon as modification and expansion packs to the smaller LWPS 3.0 are forthcoming, enabling an equal production volume but in a more modular and convenient system.⁸⁴



Figure 5. Lightweight Water Purification System. (Left to right) off-loaded assembled system and disassembled components near a truck. *Reprinted from MCRP 3-40D.14, Water Support Operations, fig. A-4 and fig 4-9.*

Lightweight Water Purification System (LWPS). The LWPS, depicted above, has a medium water production capability for hub-and-spoke operations but is considerably more versatile than its larger counterpart. It features containerized components to simplify set-up, eliminating the need for heavy equipment handling, and only requires fuel for water pumps to operate. It is designed for easy transportation on a truck, but the combined components weigh over 1,250 pounds which is not conducive to rapid mobility.⁸⁵ It is important to note that the LWPS has several configurations and can produce water from 75 to 800 gallons per hour, making it the most versatile of systems currently available.⁸⁶ System upgrades are anticipated to occur over the next few years to double production rates and completely replace TWPS.⁸⁷ Recent experimentation also demonstrated that the LWPS could operate on a truck or trailer bed, significantly improving mobile applications, but it still needs to be a codified practice.⁸⁸

TWPS and LWPS in Distributed Operations. TWPS and LWPS systems use any raw water source, pre-filtration, and reverse osmosis to make high-quality water. A large footprint is needed to produce water, and both have associated equipment required for storage and distribution, and it requires special skills to operate equipment and test water. Generally, they are offloaded for stationery setup and operations to support operations that can relocate but require additional equipment and time. In the context of distributed operations, the TWPS or LWPS, as described above, best serve at expeditionary and intermediary base locations for water resilience purposes and distribute product water in a more traditional sense to ensure water is available for operations. These systems have been the basis of water support concepts because of their reliability and time-tested ability to secure potable water for troops.

To emphasize the importance of water resilience, an Australian Government-funded water assessment was conducted in 2022 that focused on water resilience practices at Norfolk Island, located in the South Pacific (about 930 miles from Brisbane, Australia), to investigate water solutions in a drought or water emergency.⁸⁹ Water harvesting practices on the island used rainfall harvesting, bore drilling, commercial shipping, and water plant desalination techniques—all similar strategies military forces consider in expeditionary sustainment. Of the conclusions drawn, the project lead and water treatment specialist Dr. Cuan Pethram notes desalination's critical role in assured water production. This implies two essential findings relevant to Marine Corps water operations: 1) a need for larger bulk water purification systems is likely to remain intact to ensure survival, and 2) dependency on open water sources with a robust logistic distribution network is needed for water resilience. These findings demonstrate that while new concepts demand new approaches, traditional measures are relevant to provide assured solutions for water sustainment.⁹⁰

Additionally, regarding centralized water operations, Dr. Penthram's study implies that using TWPS and LWPS systems in a distributed environment may be unavoidable for extended operations as small-scale systems may incur too much risk. The findings suggest that a modification or investment in water delivery and storage systems may be more effective if centralized water treatment is necessary. While the larger units are unfit for tactical EABO employment, they may serve as essential redundancy. They may be required to be used in certain circumstances like theater security cooperation, decontamination, or humanitarian support. Alternative uses under new constructs may also employ equipment for deception purposes or at intermediary bases and, therefore, cannot be immediately dismissed based on size factors alone.



Figure 6. Platoon Water Purification System. Reprinted from MCRP 3-40D.14, *Water Support Operations*, fig. A-6.

Platoon Water Purification System (PWPS). Marine Corps Systems Command acknowledged issues of scalability and overreliance on bulk water. It recently fielded the Marine Corps' smallest scale purification unit intended to be a containerized, simple-to-use water treatment system.⁹¹ PWPS is a lightweight, reverse osmosis water purification unit that uses four functional elements: raw water, pre-filtration, reverse osmosis, and dispersed product water.⁹² The system is the first programmatic attempt to provide water treatment capability at the tactical level.⁹³ It is intended to be operated by any user regardless of military specialty and does not require a generator for power or external pumps. PWPS produces water fit for immediate consumption from fresh or saltwater sources at 18 to 22 gallons per hour and can be configured for various power inputs.⁹⁴ Accessory lithium battery packs that allow four continuous operations hours indicate that water production is sufficient for many stand-in force applications. Under optimal conditions could sustain over 40 personnel daily for a month⁹⁵ or satisfy SIF daily demand with about 2 hours of operation. Although PWPS is exceptionally compact, it consists of two cases weighing about 250 pounds, limiting vehicle transportability.⁹⁶ The system can be broken into essential components as a single case and easily fit into any mobile platform, which makes it an attractive water solution for most mobile tactical units. However, dependency on the availability

of surface source water, a required stationary setup, and a production rate that requires water management practices somewhat limit its suitability for stand-in force and EABO application.



Kit with All Components



Fresh Water Filters



Brackish Water Filters

Figure 7. Squad Water Purification System. Left to right: complete components; freshwater filter and brackish water systems. Images sourced from Marine Corps Systems Command, Program Management Office, “*Squad Water Purification System Concept of Employment and Capability Overview*” (working brief, 22 September 2022) provided to the author in correspondence 30 January 2023.

Squad Water Purification System (SWPS). At the time of this writing, Marine Corps Systems Command engineers have been pursuing technology to resolve problems with weight, resource dependency, size, and special skills problems. Currently undergoing field testing is the Squad Water Purification Unit or SWPS, which aims to create water at 60-80 ounces per minute for fresh and brackish water sources.⁹⁷ It is a lightweight, reverse osmosis water purification unit that runs raw water through pre-filtration and reverse osmosis (RO) membranes to dispense product water. The system is a pneumatic, human-powered series of filters sized for backpack carry and would sustain a group of four for three days.⁹⁸

Having no heat signature or exhaust, no electrical power demand, and simple operating procedures, the SWPS promises to support troops in ways conducive to EABO and stand-in forces. Additionally, as low-density skills become less available with the disaggregated nature of forces, SWPS can be operated by any user, making it a more versatile piece of equipment than its larger counterparts. Unfortunately, like other Marine systems, the unit requires a water source, precise water demand calculations, and material lifespan constraints that may complicate application in a distributed environment. The system may be ideal for secondary or redundant

capability as saltwater production through RO is challenging to achieve at this scale. While the system still needs to complete fielding and evaluations, the unit offers great promise for EABO and is included in the assessment of this study.

Alternatives

Foraging. Marine Corps logistic think tanks have evaluated options to reduce dependencies on logistic chains and adopted the “21st Century Foraging” notion.⁹⁹ The practice is a subsidiary-type of logistics to find vendors closer to objective areas to replace the services, supplies, or support needed to accomplish the mission.¹⁰⁰ Because unit needs are small in scale, a local economy or market can more realistically fulfill the needs of a force for stand-in forces. Foraging can be advantageous as options for water sustainment can fill critical gaps where conventional production causes excess waste or supplement shortages wherever needed. Emerging Marine Corps doctrine suggests this approach for small unit considerations, and it is also indicated in Air Force Agile Combat Employment (ACE) guidance to make use of as many sources of sustainment as feasible in an overall effort to reduce the burden of logistics and avoid heavy demands of large force sustainment in contested environments.¹⁰¹

Concerning water sustainment, foraging may consider taking advantage of local water infrastructure (e.g., domestic water services, public fire hydrants), buying bottled water, using host nation services, purchasing commercial water purification units from the market, or service agreements with partners and allies. But foraging is geographically and environmentally complicated, which makes reliability circumstantial but not complex beyond the ability to influence through reconnaissance and coordination activities. This is not to say that foraging does not yield potential benefits; in fact, foraging fosters the idea that having diverse water

support options beyond conventional water treatment is an avenue that ought to be more closely evaluated.¹⁰²

Said differently, engineers may shape the operational environment by unraveling complexity ahead of SIF engagement by defining the infrastructure, resources, terrain, and geographic restraints related to water sustainment. While an in-depth water reconnaissance effort can be a time-consuming practice, over time, it may contribute to understanding the options available for distributed forces to reveal capacity and inform capability. Such an endeavor implies re-evaluating engineer and water technician skills, which currently focus on water production with military equipment and not collecting and processing water reconnaissance information to define alternative layers of water sustainment. However, the scope of this study limits close examination of foraging but encourages continued exploration of the concept to modernize water support solutions.

Fabrication. Some studies suggest that constructing water harvesting stations with tools like fog nets or rain collectors can supplement water demands.¹⁰³ While the fabrication of passive water collection systems still needs to be evaluated, it's worth noting that the construction of purification devices like lister bags, creating solar stills to desalinate water, or constructing step wells for year-round availability an inland water source could yield benefits.¹⁰⁴ For example, ancient water harvesting included building step wells that would fill from natural rainfall, and run-off would provide a year-round water source.¹⁰⁵ Since most water treatment requires a raw water source, creating stepwells in remote locations before conflict could provide an inland source to draw water from and increase self-sustainment. Their sites may be added to engineer databases for better management of water sources at a global scale to facilitate diversified

sustainment plans. However, the construction of wells can be expensive, time-consuming, and requires advanced skills and equipment.

Additionally, delivery of supplies to remote areas and collection or local purchase of construction materials may prohibit the practical application of pre-positioning wells. But it remains that water as a necessity demands exploring every option to expand water-producing capability. This allows engineers to view water operations from a phased-operational perspective. Water resources may become more available to shape activities like infrastructure construction with host nation partners and develop cooperation plans to broaden water support operations worldwide. Likewise, partnered construction projects would improve understanding of what is available in the region, which coincides with stand-in force concepts that promote host-nation partnerships.¹⁰⁶ This implies that a closer evaluation of partner forces' water infrastructure could offer opportunities to expand water treatment solutions in austere locations below the threshold of conflict and not just in times of military crisis.

Traditional foraging is another method of survival that can produce viable means to reduce the logistical burden on troops by extending the duration of troops and may be broadly interpreted as survival tradecraft. For example, harvesting snowfall in cold climates or using plant life found in the desert or jungle environments to source pure water can be a means to survive.¹⁰⁷ It remains that foraged water sources still require purification to ensure safe consumption, but in a life-threatening situation, they may provide adequate quantities of water. Engineers would be wise to invest in training to some degree for extreme circumstances and begin establishing techniques and procedures to understand better the capacity foraging and field tradecraft have to offer. Like 21st-century foraging concepts, this study curtails a thorough

review of fabrication and survival tradecraft methods as it deserves its investigation and is excluded from evaluation in this study.

Contracting. As previously mentioned, contracting is a typical resource for the water security of troops. Generally, a requirement is generated for vetting and securing vendors and arranging logistics upon a commitment to a deployable site.¹⁰⁸ While this is a convenient method of assuring water supply, it can be expensive and a waste of resources. A RAND Corporation study in 2020 sought to understand better the risks of future Army contracting in competition phases. The study highlighted several gaps, including contractor unreliability, the need for increased military personnel resources, and flaws in low-level contract oversight.¹⁰⁹ This suggests that contract solutions, like regular logistic services, are not without risk. Further, the RAND study estimated the increased cost of supporting dispersed troops and highlighted an insufficient vetting system for vendor selection.¹¹⁰

In distributed operations, transactional contracts are an early indicator of friendly intent. They would forfeit the element of surprise and create a traceable and targetable signature. This implies a more deliberate commitment to operational security and careful vetting of vendors would have to precede arranging for contracted water support.¹¹¹ Thus, contracting as a means of sustainment in a distributed or clandestine scenario may not provide support under agreeable circumstances. Contracting can incur additional risks as increased logistic movements take up valuable supply space, and distributed units would find themselves restrained by the availability of water deliveries that increase overall risk.¹¹²

This implies that contracting water is best suited as a conditional practice to extend units' operational reach and duration. Further, the availability of contracted water depends on the area, and while local economies may have packaged water services, it is only sometimes guaranteed or

practical while engaged in conflict.¹¹³ Additionally, contracting services include exchanges with industry to establish timelines and delivery locations and assume the presence of a market that may not be available in austere locations.

The central notion of expeditionary operations is to depart from reliance on external support agencies and remain anonymous.¹¹⁴ Therefore, contacting and relying on local markets contradicts this approach. Contracting inefficiencies can be problematic, combined with the reduction in troop size (i.e., demand) and the distributed nature of stand-in forces suggesting that evaluating contracting services as an alternative means for engineers to provide water effectively is unsuitable. While the option will continue to be considered in layered logistics, the profile and implication of using contracting as a principal means are undesirable.

However, contracting does not exclusively entail packaged water, as it can also be used to secure commercial purification devices. This option has been employed in the Special Operations Force community and other military circles for a long time but is without standards and typically award individual unit purchases for unique purposes. While a market may not always be present, there may be circumstances where it is operationally feasible to depend on commercial capabilities to provide water.

In instances where operations are overt, temporary, or merely convenient, using contracting in this method may be a viable option but require a degree of oversight to ensure product selection is suitable in terms of water quality and production capability or to ensure features and characteristics can meet the needs in demand. In the research article, *Small-unit Water Purifiers for Remote Military Outposts: A New Application of Multicriteria Decision Analysis*, authors Lauren Koban, and Jaqueline Gibson proposes developing a multi-attribute value model that can aid the selection of commercial equipment to facilitate water purification

unit selection of commercial equipment. Adapting this approach to the greater force would optimize equipment selection based on the contexts of the given need and provide a framework for multi-factor equipment selection that may lessen equipment demand burdens by aligning the right equipment for the right need.¹¹⁵

A water equipment selection framework would benefit the force and prevent sole-sourcing equipment, which reduces stress on production lines. In the event of a spike in demand, such a framework would provide suitable alternatives if manufacturing bases cannot support extremely high or low demands. This recommendation, while helping to guide commercial off-the-shelf purchases, does not advance the purpose of this study and is not included in the evaluation.

Interservice Support. Interservice support consists of utilizing another component's means of providing water to support operations. As modern warfare suggests, the Marine Corps is gravitating toward joint operations, and interservice support is essential in securing water in the future environment.¹¹⁶ Further, as geographic combatant commands consist of many different services, it may be practical, efficient, and economically sound to use others' resources and capabilities to complement operations in pursuit of mutual goals.

For the Marine Corps, the greatest interservice support would be from the Navy. Naval vessels carry reverse osmosis on their vessels and have logistics teams on board to sustain forces both afloat and ashore. Vessels can act as logistic connector craft to support troops ashore and, in this instance, could resolve problems with water storage and distribution problems. However, vessels are very observable platforms tracked and traced by opposing forces.¹¹⁷ Despite senior leader suggestions as a viable option, concealment of water-borne craft is not easily achieved. It

is likely envisioned to assume sustainment roles in a semi-permissible environment or contribute to sustainment as a layered, intermediary logistic connector.

In the context of expeditionary advanced-based operations, vessel support would be in an intermediate zone outside of weapons engagement areas and limited in their reach by requiring water access or established landing sites to support a logistical chain. Further, the wide distribution of forces may render such options considerably restricted, and vessels would be resigned to constant resupply operations not conducive to tactical sustainment.

Engineers from all branches employ a broad range of planning, service support, and careful logistic coordination for treating, testing, storing, distributing, and issuing water to ensure critical life support.¹¹⁸ This implies that the joint, interagency, and multinational community should be a significant consideration when planning operations. Though sustainment solutions are often resolved through common-user logistic channels, these considerations exceed the scope of this study. Still, they are encouraged to be thoroughly investigated during mission planning and in pursuit of emerging operational constructs.

It remains that distributed operations still require tactical water sustainment that is conducive to maneuver with less of a tax on the warfighter and support structure.

Methodology and Research Evaluation Criteria

This study uses the problem/solution research framework to assess the feasibility of Marine Corps engineers' employment of water harvesting technologies to provide essential sustainment to distributed forces in austere locations effectively. The methodology permits the author to evaluate the suitability of employing atmospheric water generators as an alternative solution to provide potable water to tactical teams in near single-digit quantities spread out over

long distances. This method also allows the comparison of quantitative values between current systems and a commercial water harvester using the combined criteria of physical attributes, stealth, the economy of scale, and resource dependencies. Evaluating this data permits the author to extrapolate qualitative value judgments concerning water support operations in the context of the Marine Corps' shift in strategy.

Evaluation criteria will review four key measures: physical attributes, stealth, the economy of scale, and resource dependency. All criteria will compare current and emerging Marine Corps water treatment equipment with the Gyrene Mangrove atmospheric water generator. The Mangrove is the selected sample because of Air Force mirrored approach to Marine Corps distributed operations and service investments in atmospheric water generation that was awarded first place in a 2022 Air Force service-wide call for innovation.¹¹⁹

It is important to note that weighted values are not intended to reflect an overall “winning” score but to provide insight into equipment suitability in distributed maritime operations, expeditionary advanced base operations, and stand-in forces. Said differently, water systems evaluated are not in competition with one another but are an attempt at associating a quantitative value to assess suitability for emerging Marine Corps operations better.

The first criterion will consider physical attributes of size and weight of system components as these factors are the most observable features. These are essential measurements because they determine how manageable a system is in terms of effort to establish or relocate. Additionally, they permit evaluation of the following criterion—stealth. Stealth is necessary for clandestine forces such as those intended for SIF missions and roles. It will be assessed regarding observable signatures such as noise, heat, visual detectability, means of concealment, or factors that may indicate military presence. Due to the limited or unavailability of information, such as

the degree of electromagnetic signature or infrared analysis, this criterion will be assessed in simplified terms.

The economy of scale will be evaluated next to express the water production rate to compare system versatility and efficiency. The water production rate will be captured in terms of time and will assess the amount of water produced and the type of water source the system draws from. This metric drives the number of personnel that can be sustained, thereby indicating overall capacity. Lastly, resource dependencies such as fuel consumption, associated requirements for transportation equipment, storage equipment, or geological conditions like open water sources and relative humidity will be measured to gauge versatility further and make value judgments based on resource constraints.

Analysis and Results

Overall distributed operations suitability of the Mangrove system is at least on par with current systems but superior when considering the combined power harvesting, optional water harvesting, and reverse osmosis (RO) water treatment capabilities. The Mangrove's atmospheric water generator (AWG) provides conditional benefits that place it in its own category. Namely, the ability to create water while on the move and independence from relying on surface water features to make water is a game-changing technology conducive to rapid mobility and freedom from logistic chains. The Mangrove AWG water capabilities would satisfy water demand for small, distributed forces in the circumstances for very small elements. But the reliance on environmental conditions limits fruitful application in all climates. Interestingly, this shortfall is offset by the onboard RO system and power supply and corroborates the notion that water resilience for distributed forces is better served with multi-purpose systems. This suggests that

the combination of AWG and RO offers versatility to satisfy distributed operations water demands with additional benefits currently not in Marine Corps inventories.

From a decentralized operations perspective, Mangrove's strengths lie in its versatility to store, produce, and distribute water from either atmosphere or surface.¹²⁰ Said differently, having the *option* to draw water from the air rather than solely relying on AWG harvesting is the advantage of providing water closer to the point of need. Critical shortfalls are in the size and weight of the system, which precludes use by foot mobile troops in the same manner as other water purification units and is its most limiting factor. However, as the Mangrove is integrated with mobile platforms, the need for material handling equipment or hand-carry is eliminated but then assumes the platform's constraints.

This may affect stealth as a larger platform with communications and engine parts will emit a greater signature. This indicates mobility, concealment, offsetting operational times, and masking specific components are needed to satisfy force signature management practices in water support equipment.¹²¹ Although AWG incurs a more significant resource commitment by necessitating pairing with a vehicle and has situationally dependent tradeoffs, the power harvesting capabilities and onboard sensors open other avenues to expand utilization as a stand-in force tool by providing a means to store energy and simplifying conditions for rapid displacement and overall self-sustainment.

Evaluation Criteria	Weight	TWPS		LWPS		PWPS		SWPS		MANGROVE	
Physical Attributes	2	1	2	3	6	4	8	5	10	3	6
Stealth	3	1	3	3	9	4	12	5	15	4	12
Economy of Scale	3	2	6	5	15	3	9	3	9	4	12
Resource Dependency	2	1	2	3	6	4	8	5	10	5	10
Total		5		14		15		18		16	
Weighted Total			13		36		37		44		40
Comments:											

Table 6. Evaluated Criteria, Weighted Matrix. (Format obtained from *Campaign Planning Handbook: Academic Year 2019*, Carlisle Barracks, PA: U.S. Army War College, 2019, 113.)

The above chart expresses values of criterion and is weighted under stand-in force (SIF), expeditionary advanced-based operations (EABO), and distributed maritime operations (DMO) conceptual frameworks. The weighted values express that Mangrove performs as a link between the small, hand-powered Squad Water Purification System (SWPS) and the lightweight, multi-power sourcing Platoon Water Purification System (PWPS). PWPS and SWPS satisfy water demand requirements with greater efficiency regarding the size and rate of water production. Still, the Mangrove's air-to-water feature and all-in-one design is a niche pairing of capabilities that provides options for power and water in a more straightforward form and offers an ability that PWPS and SWPS cannot perform.

Results indicate that the Mangrove AWG demonstrates strength by pairing water treatment systems with power, water storage, and dispensing capabilities. Operational restraints associated with weight and size limitations are offset by incorporating components in vehicle 'dead space.'¹²² This enables creating 'water on the move,' which no Marine Corps system is currently capable of that enhances mobility but also increases water dependence on equipment availability. For this reason, Mangrove capabilities may best be served to integrate AWGs in the

existing family of tactical vehicles to enable self-sustainment and decrease logistical burden throughout an area of operation. Below is a review of the criteria and discussion.

Physical Attributes

Operations accustomed to centralized operations permit hub and spoke operations that capitalize on equipment efficiencies. Unfortunately, this often entails large pieces of equipment that require material handling equipment and stationary processes from which logistic lines of communication can expand. System size and weight create logistic challenges as it dictates the physical constraints and requirements to achieve a function. Distributed operations entail frequent movement, occupation of temporary sites, and rely upon speed, simplicity, resilience, and using resources closest to the forward edge of the battlespace, which undermines standard practices.¹²³

An ideal water solution would require no special equipment or additional requirements. While it may be achievable to use host nation support, contracting, or other means to provide water, these services are only sometimes in place or available. Additional concerns for operational security or time-sensitive requirements may also prevent relying on external sources for support.¹²⁴ As tactical task elements in a distributed environment must maintain high mobility, attributes of weight and space have a different premium in equipment selection. Therefore, a water system that can be carried by an individual and conform to foot-mobile combat loads is an ideal solution.

The first criterion is comparing physical attributes to understand better how the Mangrove compares to other water treatment systems. Appendix A-1 compares physical traits that look at size and weight to assess the ease of management and the degree of effort needed to

establish, move, and sustain a water site with limited or no infrastructure. Regarding physical attributes, the Squad Water Purification System (SWPS) is the closest to an ideal system.

Weighing 27 pounds, SWPS is light enough for individual carry and small enough to fit a combat load.¹²⁵ The SWPS can also spread load its components to distribute the weight among troops for more accessible travel and has no restrictions for transportation. The SWPS has no work area requirement and dispenses water to individual canteens or water packs, so it incurs no added costs in terms of water storage. The superior dimensions and extreme lightweight of SWPS, while very manageable, does so at the expense of not being capable of purifying salt water. As expeditionary operations entail operating in littoral regions, it is a fair assumption that the size and weight tradeoff can be problematic. Additionally, the SWPS is not intended as a primary means of treating water but may serve very well as a precautionary water security source.

Mangrove is essentially a mobile water site that requires no time to establish a site when using AWG-only features. The reverse osmosis (RO) unit can produce water within minutes without an increased work area or demand for additional equipment if necessary. These attributes highlight the appeal of Mangrove as a self-contained mobile unit that assumes a 3.8 cubic foot area and is conducive to providing water at decentralized locations,¹²⁶ of which can be rapidly displaced if required. Because the Mangroves uses an internal storage tank, it resolves issues with secondary containment and demonstrates that the all-in-one approach to water support simplifies operations. Thus, the effort needed to establish, move, and sustain water operations demonstrates advantages in speed and ability to provide water in a decentralized fashion.

An argument can be made that the PWPS is equally capable, as the system is easily transported and produce water within minutes. The PWPS requires no peripheral operating

equipment because it disperses water directly to user canteens, water packs, and jerry cans.¹²⁷

The PWPS is about 200 pounds less than the Mangrove and quickly moves from one platform to another, given the available cargo space of five square feet. Its small size can be reduced to essential components in one box and requires minimal training for setup and take-down, which can be achieved in minutes. However, the difference in weight is negligible as all systems, apart from SWPS, are prohibitive of troop carry. The PWPS requires a static footprint to produce water, making it less versatile than the Mangrove.

The Mangrove compacts peripheral elements like secondary containment, distribution nozzles, and pumps, reducing the overall required work area, requiring only an intake hose from a raw water source to feed the RO system, or none if using only the AWG. If the system remains mounted, no additional heavy equipment is needed, and water production is as mobile as the platform it is mounted on. The Mangrove can integrate AWG, RO, and power system modules into vehicle dead space, eliminating the need for material handling equipment and implying physical space requirements can be reduced below the 3.8 cubic feet of space it needs to operate. Of note, the next generation of Mangroves is anticipated to take on modular qualities found in PWPS and SWPS systems to enable more effortless transfer and spread loading of capabilities for more versatility, which may improve its suitability for distributed operations.¹²⁸

This indicates that there are benefits to exploring options for producing water while mobile, which may be possible with existing systems if a raw water source and product water storage tank are made available. The Mangrove is an example of integrating water treatment capabilities within mobile platforms that may help offset water demands in austere locations. Additionally, closer evaluation of reducing peripheral equipment and work areas in the manner that SWPS, PWPS, and Mangrove achieve implies that point-of-use water treatment systems

must aim to produce water intended for immediate consumption and bypass secondary containment or re-storage practices.

Stealth

The element of surprise is a common warfighting principle among all services and is a critical component of stand-in forces concepts.¹²⁹ For distributed forces to be most effective, they must be able to hide troops and “reduce [their] signature to avoid detection” to achieve a tactical advantage and encourage opponents to expend more resources than they can afford.¹³⁰ The central philosophy of stand-in forces and distributed operations disaggregates forces throughout an area of operations for enhanced all-domain awareness that can find, fix, track, target, engage, and assess before an opponent can do anything.¹³¹ To do so, distributed forces must make exceptional counter-reconnaissance efforts to avoid detection by understanding opponent reconnaissance capabilities and managing the operational signature of their troops.¹³²

While stealth technology has a long history ranging from early concealment practices and materials designed to reduce detectability to improving the effectiveness of critical assets, its application on the tactical scale has recently gained relevance. The rapid technological growth and employment of intelligence, surveillance, and reconnaissance assets in all domains have changed operational circumstances that increase the value of stealth.¹³³ As bulk-water systems require generators, pumps, and heavy equipment and are accustomed to centralized and relatively static operations, the issue of stealth can be a significant downfall in operating with current equipment. Therefore, the second criterion evaluates the qualities of stealth as it relates to visual, audible, scent, and electromagnetic signatures.

The feature of stealth is highly dependent on physical attributes, as operating clandestinely requires avoiding all detection modes. As electromagnetic signatures could not be

sourced, the assessment was completed by evaluating the presence of signatures, footprint, and methods of concealment required to avoid detection.¹³⁴ The ideal water treatment system would have no signature even when operating and would be easily concealable and able to move without restraint.

Unsurprisingly, the SWPS system has the most desired traits as it is manually operated, extremely small, and has no heat or exhaust that can be detected. The tradeoffs are identical to the previously cited criteria as it requires a water source, cannot treat salt sources, and the lifespan of its filters, while unavailable, is likely to be considerably lower than other water treatment systems.¹³⁵ Though imperfect, the SWPS may be a very favorable option to employ in the distributed environment, especially for periods of short duration.

Comparatively, the PWPS has many qualities well suited for stealth. The PWPS is powered by a battery or auxiliary electrical input and has very small components contributing to ease of concealment. While PWPS employment requires static positioning, it is highly mobile and can be disassembled in minutes. However, using the PWPS assumes it is paired with a trailer or vehicle and essentially assumes that same signature.

The Mangrove's greatest stealth attribute resides in integrating with mobile platforms that enable displacement. Like the PWPS, but to a greater degree, the Mangrove assumes the same profile as the vehicle it is attached to and increases its overall signature. The Mangrove power module can be employed to reduce heat and infrared signatures, but internal components of the AWG operate on mechanical condensation. Signature masking can avoid detection, and traditional cover and concealment practices can reduce detectability. Mangrove operates at 55 decibels (conversational volume) and runs from an electrical power bank with no odor.¹³⁶

Mobility is an essential attribute that could be more conducive to current water equipment. Most water equipment is treated as cargo and requires other components to complete a setup that uses cargo space and requires several steps to make water. Procedures required to identify an appropriate surface water feature, move to the source, perform water production, store, and return to the point of origin to distribute product water can be time-consuming. The necessity to draw intake water from a surface water source also impairs versatility and affixes troops to a site exposing them to observation and limiting options to locations at a location. These common system shortfalls highlight the significant advantage of Mangrove as they can create water while on the move. Said differently, when mounted task elements are provided windows to move from locations, they can reduce detection probabilities by avoiding static positions and creating water when moving between locations.

A significant review of engineer equipment is needed to understand potential signature vulnerabilities of current equipment better. Given the increased importance of signature management, traditional camouflage techniques and materials should be modernized to incorporate radar scattering and thermal reduction materials to improve concealment efforts.

Economy of Scale

The *Tentative Manual for Expeditionary Advanced Based Operations* defines economy as “eliminating unnecessary duplication and redundancy while still providing the required support.”¹³⁷ From the perspective of distributed operations, decentralized water production facilitates that end state. However, the change from large force presentations to small units that must be highly decentralized challenges the suitability of bulk water practices.¹³⁸ Issues arise as the number of people that require support is significantly lessened, and the change from centralized to decentralized operations reshapes equipment suitability. As a result, the balance of

supply and demand is upset and indicates that optimal systems that scale water production following mission demands are small and deployable. Over the years, the equipment has undoubtedly become smaller, lighter, and broadened production scale. Still, the current inventory must scale production levels below platoon and company size even further to match equipment capabilities with distributed force needs.

The third criterion of scale evaluates the versatility and efficiency of systems against a day of water supply assumed as three gallons per day per person because it reflects the average demand for all climates.¹³⁹ Although new concepts may include dispersing individual operators in remote locations, a distributed force of 12 is a standard unit of action for a distributed operations assignment. It results in a total daily demand of 36 gallons per day.¹⁴⁰ The low daily demand highlights the core problem as water treatment capabilities provide unnecessary excess that systems cannot easily scale below the company level without resorting to practices in storage and redistribution used in centralized bulk water operations.

This assessment compares systems in terms of production rates and reveals that the Lightweight Water Purification Unit (LWPS) demonstrates the greatest flexibility in scalability.¹⁴¹ LWPS water production range is versatile enough to meet the demand of a distributed task element in less than half an hour from a saltwater source or just over 17 minutes for freshwater in its smallest configuration. The LWPS can achieve the same in under six minutes in its largest configuration.¹⁴² This indicates scalability may be best served by modular configurations, an attribute unique to LWPS but would benefit other water treatment systems. The feature is vital as mission demands are unpredictable and may lead to significant water increases, which other systems cannot easily satisfy, and validates the need to keep current technologies in the Marine Corps inventory. Excess product water can be avoided by curtailing

operational time, and low-flow pumps can dispense water to jerry cans or individual water packs. However, scalability comes at the price of additional personnel, half an hour of set-up time, a static location, the need for water storage, and a truck or trailer to carry its components.

Another option might be an individual unit that can produce water on demand from any source. Said differently, scaling a system for individual use would be ideal for decentralized operations. Still, as SWPS demonstrates, very small water treatment using RO filters has its limits in the type of source water it can purify. Alternatively, the Mangrove AWG adds the atmosphere as a water source, which increases its versatility. But the AWG has a minimum production rate of 1.2 gallons per hour,¹⁴³ meaning it falls 7.2 gallons short of meeting daily water demand using AWG features only. To satisfy the demand using AWG only, the internal tank can be filled before a mission, fulfilling the minimum demand for 2.7 days. Likewise, the Mangrove RO system can augment water production, assume the primary water-making role, and meet daily water demand in under two and a half hours. Thus, the Mangrove's economy is balanced by combining its AWG, RO, and interior storage features.

The economy of scale is troublesome to assess, as the most efficient systems are also the largest and least versatile. The Mangrove AWG has lower production rates but offers more versatility as a stand-alone system and provides options to draw from other water sources with near similar efficiency as existing small water purification units. The digital onboard sensors provide data for intelligent control over water production that provides the status of operations to facilitate planning and inform water production estimates or calculate water conservation efforts with precision. The Mangrove has more universal applications requiring no setup and operating procedures geared toward any user, implying less need for specialized skills. However, it

requires more time to meet daily water demand than current water treatment systems and still depends on relative humidity to produce water from the air.

The modular configurations that LWPS offers and Mangrove's combination of a broader array of technology suggests versatility and efficiencies can be achieved by integrating AWG capabilities in existing equipment and exploring more flexible options for water storage and sensor technology integration.

Resource Dependency

The last evaluation criterion compares the depth of additional resources required for water support operations. Bulk water operations pose a practical problem to distributed operations primarily due to the number of conditions and level of commitment needed to support troops.¹⁴⁴ Complicated processes need skilled labor to manage equipment, and timing must align with logistic employment concepts to ensure the delivery of essential supplies and equipment. Fuel and other equipment are needed to operate equipment, and additional materials or equipment are necessary to sustain operations. In short, resource dependencies increase logistic burdens on the greater force and call for simplification through other means to find a more suitable means to provide water to distributed forces.

The ideal system would require no additional resources or special skills and be deployable at an individual level. Appendix A-4 compares existing water treatment equipment with the Mangrove AWG to assess suitability for distributed operations. Dependency on surface water features is included as it determines whether water treatment is feasible at a location and indicates an associated risk as it may dictate where or how often troops return to an area to collect water. The human resources needed to support a system increases the cost and demand required for the capability. The degree of skill to operate equipment likewise indicates the level

of investment from a training perspective and reflects the capacity and simplicity of a system. Other important factors like material handling equipment, secondary containment requirements, and the need for supplies like chemicals, maintenance parts, and filters also indicate the effort needed to sustain operations. A broad comparison of power sources is assessed as the source of energy necessary implies additional logistic demands and can easily constrain options in a distributed environment.

The most resource-intensive systems are the Tactical and Lightweight purification systems. It is unsurprising as these are the most extensive variety of systems, with the most significant number of components, and are mechanically complex. High water production rates result in additional equipment and materials. They require considerable pressure to move water through their filter systems, increasing power and fuel consumption. Comparatively, the Platoon Water Purification System (PWPS) can draw power from various sources, including solar panels, batteries, and auxiliary power lines found in common equipment.¹⁴⁵ This quality contributes to the versatility of the PWPS and demonstrates the importance of compatibility between existing resources and water treatment tools that can simplify sustainment solutions. Another key PWPS feature is the ability to dispense water directly to users, eliminating the need for secondary containment systems and lessening requirements for peripheral equipment.

However, the Squad Water Purification System (SWPS) is the least resource-dependent system. Requiring only a brackish or freshwater source and manpower to force water through filter membranes, the system shows how a deployable hydration solution can be achieved without advanced technology or complex logistical support chains. However, the dependency on an open water source highlights Mangrove Atmospheric Water Generation (AWG) 's critical advantage over all other systems—making water from the air.

The Mangrove strength is clearly in the versatility of adding AWG as a water treatment method, making it unique and unlike anything in the Marine Corps inventory. Training beyond startup instructions is aided by a digital interface and can be operated without the need for water technician skills. The system uses an 11kWh battery bank that harvests energy from the host vehicle alternator or auxiliary power source, including hybrid or renewable energy sources.¹⁴⁶ The AWG working on battery power alone will operate for about 8 hours without any external inputs and would satisfy water sustainment for a team of three for a day. If solar energy is available, the system could operate without vehicle support to create water, eliminating the need for fuel for extended periods.¹⁴⁷ The reverse osmosis system can run on battery power alone for over a day, making over 408 gallons of water in the same period.¹⁴⁸ With renewable energy attached, it can perform for elongated periods and serve as a dynamic sustainment solution for distributed forces. All required peripheral equipment like water storage and dispensing is within the component, which fulfills an overall intent to create a one-stop, multi-capable system to serve various sustainment needs—namely power and water for remote units.

The Mangrove's weaknesses are in its weight which lends itself to the logic of integrating the system into mobile platforms. While stand-alone versions exist, it would require heavy equipment to on/offload the platform and take on a static, albeit expeditionary, profile. The Mangrove's main AWG feature also depends on climate relative humidity (RH). Minimum 1.2 gallons per hour production rates require a 60 percent RH level.¹⁴⁹ Recent experiments with the 52nd Civil Engineer Squadron have recorded production that exceeds those levels but maintains production rates generally sufficient for teams of nine and below in most environments. It is important to note that Mangrove can be configured to use metal-organic frameworks (MOFs)

that use sorbent materials and a combination of metals that attract water in very low humidity environments but does so at the expense of energy exchange.¹⁵⁰

The AWG feature will draw water at any humidity level but at mostly inadequate volumes below the 50 percent RH range, which is the main advantage of having an onboard reverse osmosis system.¹⁵¹ To draw water below even the 25 percent RH range in quantities to support life, the system would expend almost triple the energy than the normal active condensation process. Said differently, the tradeoff of low-humidity water production occurs at the expense of power. It is feasible with a solar farm, micro-grid, or locally harvested electrical energy that Mangrove can be modified to produce water at 25 percent or below RH values. However, it would require permanent or semi-permanent power sources that undermine the goals of highly mobile and expeditionary units.

The all-in-one configuration and combination of AWG technologies that the Mangrove feature suggest suitability for distributed operations where mobile platforms are used. Integration with precision fire platforms like the High Mobility Artillery Rocket System, common troop carriers like the Joint Light Tactical Vehicle, and even Ultra-Light Tactical Vehicles could enhance autonomy and prolong self-sustainment in austere locations. As previous criterion evaluation also demonstrates, the utility of combining power harvesting, AWG, and RO water treatment systems provides options beyond what Marine Corps inventory currently offers. Future designs are encouraged to combine technology and capabilities that provide a range of options and therefore be more capable of adapting under broader circumstances.

Implications of Results

To understand how Marine Corps engineers can most effectively provide water to distributed forces in austere environments, this study framed the operational requirements and define how it differs from conventional sustainment concepts. The difference between sustaining 180 personnel at a consolidated location and providing water for several teams of 12 disaggregated across various locations. Without question, the tax on sustainment efforts is too great because equipment size, weight, and resource dependencies create limitations that prevent a single solution to complex and environmentally dependent circumstances.

Results indicate engineers must maintain a broader family of water support systems scalable from the individual to the large formations to meet a range of military operations, including distributed operations. Current and emerging water harvesting technologies promise to protect distributed forces by introducing new capabilities to create water while moving and can offset demands in most environments by breaking complete dependence on available surface water. Atmospheric water generation (AWG) can be viable for small-scale sustainment and enhance the lethality of stand-in forces, but most appropriately for mounted parties or semi-permissive environments. Alternatively, AWG may create potable water in locations that do not have a high demand for mobility and may be a valuable tool in circumstances that may require both traditional operations and novel EABO engagements.

Research indicates that while the current inventory could be better, adequate water support for distributed troops is feasible but requires additional equipment, in-depth planning considerations, and tethers to an open water source. The newly fielded Platoon Water Purification System (PWPS) and the tentative fielding of the Squad Water Purification Systems (SWPS) have capabilities that satisfy small force needs and are a feasible means to sustain

distributed troops, but with a similar requirement to be paired with a mobility platform. These systems may be the preferred water treatment modules until technology can produce individual-sized water production units.

The use of AWGs is nearly in a category of its own due to its unique characteristics. It may help advance agendas in breaking patterns and modernizing equipment to increase options at the front lines where needed most. This suggests that water support operations are best served by aligning equipment per specific missions or in environments with higher relative humidity. While assessment of a particular AWG platform was not the aim of this study, results indicated that the Mangrove AWG shows favorable results because of the pairing of AWG and reverse osmosis (RO) on a single platform. Ultimately, this suggests that AWG can bridge gaps for water sustainment problems that new or emerging equipment cannot fill and circumvent potential friction points by incorporating existing RO technology into systems.

Table 7 summarizes this assessment and concludes that AWG, when paired with RO, is beneficial as it broadens the range of options. The commercial Gyrene Mangrove sample was initially selected for AWG qualities but revealed that the combination of several technologies with AWG was most beneficial and contributed more to reducing workspace and setup times and enhanced the simplicity, mobility, and utility of the system than AWG alone. Thus, further research into pairing technologies is warranted to identify areas where engineers can enhance water support operations. For example, water storage, dispensing, and monitoring repeatedly were key benefits or restraints in operations. And component modularity and compatibility were also positive traits. This suggests modernizing storage and water management tools can enhance sustainment in austere locations. Modular raw and potable water storage and low-pressure

filter/dispensing systems could be additional areas that may improve operations to expand options for existing equipment like the Lightweight Water Purification System (LWPS).

System	Pros	Cons	Distributed Operations (DO) Implication
TWPS	-Reliable to treat all open water sources	-Heavy and large footprint -Resource intensive -High maintenance and special skills -Static position required	-Intermediary base redundancy Measure -Deception tool -Use to expand operations beyond DO
LWPS	-Multiple configurations -Transportable by vehicle -Modular components -Reliable for all open water sources	-Heavy & static operations -Needs special skills & resupply -Production rates suitable for >100 persons	-Intermediary or water resilience measure -Employ under expanded operations conditions
PWPS	-Uses a variety of electrical sources -Independent battery bank available -Hybrid/renewable energy accepted -Compact and vehicle transportable -Dispenses to user at small scale	-Requires vehicle for transportation -Static position required -Requires open water source	-Mobile units in areas with multiple open water features
SWPS	-No power requirement/no skills -Man-portable & no 'signature' -Makes water on demand at point-of-use -No 'work-area' required -Components can be separated	-Requires open water source -Fresh and Brackish only -Limited filter lifecycles	-Foot mobile applications for short-duration missions -Redundant water security measure
Mangrove	-AWG capable/water 'on the move' -Internal water storage tank -Combines power harvesting/power bank and "smart" sensors -Digital 'plug-and-play' interface -Hybrid and renewable energy compatible -Small 'work area' -Onboard reverse osmosis system -Low maintenance and no special skills	-Weight requires vehicle for transportation -Low AWG production below 50% relative humidity -AWG high power demands -Assumes 'signature' of vehicle	-Highly mobile units in uncertain environments -'Drop-in,' temporary or semipermanent bases -Integrate into platforms and modify for additional configurations -Deploy for shaping security cooperation -Implement sensors as domain awareness tool
TWPS – Tactical Water Purification System		LWPS – Lightweight Water Purification System	
PWPS – Platoon Water Purification System		SWPS – Squad Water Purification System	

Table 7. Water System Pro/Con Summary Chart. Collation of the author's observations.

While atmospheric water generation may provide an important function, it must be more inclusive. Additional research into supplemental power, storage, and water testing equipment conducive to prepositioning or long-term storage may help offset demands further. Its dependence on an energy source and a requirement to be paired with a vehicle due to size and weight imply certain limitations that must be considered during equipment selection processes.

However, AWG alone as a self-standing capability offers freedom of maneuver to distributed forces and should be a significant factor for distributed operation planners. This quality benefits the troops, even if only suitable for high-humidity environments. The capability must be exploited to help new operational concepts and expand sustainment options for troops beyond what has been traditionally employed. For this reason, Marines can improve current sets and must partner with commercial specialists and research and development agencies to integrate AWG capabilities into existing equipment sets and mobile and logistic platforms.

Modernizing water systems with internal water testing, system diagnostics, and environment assessment sensors may reduce manpower burdens in post-production water inspection processes. Utility companies have long used facility-related control systems and programable logic controllers to monitor, meter, and control equipment to aid industrial automation, maintenance, and management of utility equipment spread over long distances. Early development of automated systems for any user, regardless of military specialty, may also reduce specialty skills in operating and maintaining equipment. The Marine Corps must integrate these technologies to facilitate complicated water support equipment planning, analysis, and management. Doing so would enhance engineer battlespace awareness, inform water management practices, and facilitate predictive logistics for the management and sustainment of troops. Information may be stored in databases to identify trends and potentially reveal risks before consequences occur or enable monitoring of local conditions for environmental factors like relative humidity to indicate warnings of low production rates that may cue actions to find other water sources.

Technology and material science constraints reinforce the notion that size ultimately drives productivity. The Marine Corps has followed this example but misplaces technology

investments that value efficiency over effectiveness. Stated another way, water production equipment assumes that its customer would be mass formations committed to major combat operations in a decisive engagement and not distributed low-signature forces. Research implies that equipment sets cannot forgo bulk-water approaches to retain water security in the performance of traditional missions but must also invest in small-scale solutions to support new concepts. To reconcile the differences, research indicates that engineers must adopt water production capabilities by widening their aperture to employ commercial technologies and pursue AWG as one such method.

Assessment of implications concerning other variables

Several elements must be better served in follow-on research, like water quality analysis, peripheral water equipment for storage and transportation, training, costs, and other normative concerns related to logistics and water support operations. These considerations raise other problems best served in follow-on research.

Power. Like water, power demand is needed to operate the equipment. Aside from low-pressure pneumatic systems like the SWPS, water foraging, and passive water harvesting options, power is required to use water purification equipment. While the Marine Corps and other services have invested in power generation, harvesting, and storage equipment and may pursue power-foraging capabilities, it remains that a water production unit capable of delivering water at scale, regardless of the type of filtration used, will need a power supply. Generators can be heavy and release electromagnetic and heat signatures undermining desired clandestine attributes. Photovoltaic power generation systems (i.e., solar power panels) offer some promise in low-power demand systems but also come at the cost of maintenance, power storage and distribution, and detectability concerns. Subterrain structures, thermal and electromagnetic distribution

camouflage, hydrogen fuel production systems, and others may serve as future sources. Said another way, water treatment capabilities must incorporate a whole-of-system approach to comprehend impacts fully.

Fuel. Small, geographically disparate units operating equipment and maneuvering independently in the battlespace calls for an equally small and distributed fuel supply concept of employment. Alternative fuels like hydrogen and photovoltaic (e.g., solar panels) may offset fuel consumption and enhance the duration of distributed units. Fuel conservation practices, too, may relieve logistic supply chains. Still, the relationship between fuel and water treatment capabilities must be considered a complete system to assess the impact atmospheric water generation can have on establishing a more deployable hydration capacity within the Corps. Cache's, intermediary base support, autonomous delivery systems, and artificially intelligent systems that can manage capabilities and capacity for predictive sustainment modeling suggest some promise in expanding engineer capabilities to sustain austere forces better. Still, developing employment concepts for distributed water support operations remains contingent on fuel support operations.

Cost. As with all programs, budget is a driving factor in investment decisions. Access to nascent capabilities abounds with unlimited financial resources, but competing interests and costly research and development projects often limit the practical application of developing technologies. Assuming three to five hundred atmospheric water harvesting-capable systems would be needed to augment distributed operating units Corps-wide reasonably, investment into a new technology of this nature may exceed tens of millions of dollars. This represents significant cost-benefit decisions to be made in exchange for capabilities that are fundamentally already present. The critical tradeoff would be autonomy and the ability to produce product water in high-humidity environments like the Indo-Pacific region. Therefore, a more practical

approach would be the experimentation of ruggedized atmospheric water generators with units stationed or trained and exercised in selective areas. Before total commitment at a fraction of the cost and permitting continued improvement to systems, Marine Corps engineers can selectively test equipment and functionally rehearse distributed water sustainment operations in advance of future employment concepts. It is important to note that the correct system may also provide significant cost benefits. Air Force specialist and Project Arc Water lead, Senior Master Sergeant Brent Kenney, estimated a 98% efficiency gain using a water harvester with a solar panel array.¹⁵² Most of this is because of saving cargo space reserved for water.¹⁵³

Water Quality Analysis. Water quality analysis is essential to water operations, as abiding by results before consumption will avoid risks to life, health, and mission. The Water Analysis Quality System ensures that the proper chemical balance is present. Unfortunately, these systems are external to water production and storage units, requiring water technicians and medical personnel to inspect all product water physically. This can be a limiting factor in providing water as engineers cannot always be in all places where water is produced. It implies that additional personnel, technologies, or circumstantial considerations like chemical or biological threats must also be considered for future research.

Conclusion and Recommendations

Conclusion

In 2019, Marine Corps Commandant General David Berger outlined his broad intent in the *38th Commandant's Planning Guidance* to alter the Marine Corps' focus from a global response force to a distributed maritime stand-in force. Marine Corps engineers primarily rely on the equipment's capabilities to provide essential sustainment, both large and small. However, current equipment sets appear best suited to provide water support to large troop formations,

challenging Marine Corps engineers' ability to effectively provide water to distributed forces, especially in austere environments. This research indicates that atmospheric water generation offers a distinct but conditional advantage to providing water to dispersed troops in austere environments mainly due to its ability to create water without a water source and its capacity to make water while moving. The weight and size require vehicle support, and dependence on environmental conditions are limiting factors that preclude its use for all environments and foot mobile operations. Still, the value of blending capabilities with other technology and existing platforms may improve engineers' ability to support a wide range of water support requirements more effectively. Equipment sets must diversify and advance with the availability of commercial technologies to support distributed military formations better.

While the findings of this paper are inconclusive, the research indicates a need to diversify water equipment with commercial capabilities to deliver water and integrate existing AWG technology in mobile and logistic platforms. Importantly, Engineers must sustain medium and large-scale bulk water practices and reshape storage and transportation methodologies for effective water resilience in austere locations. Results indicate that pairing AWG and RO may provide flexibility to work between traditional and emerging operational constructs. Requirement scoping and investment in water harvesting technologies are also necessary for water security.

Due to the wide-ranging disparity of requirements, research also indicates that Marine Corps engineers are best suited to embrace planning functions for joint intelligence preparation of the operating environment by defining existing water capabilities and limitations. Joint water reconnaissance efforts that capture water sustainment capabilities, capacity, and identification of military, commercial, and host nation resources would improve common operating pictures and clarify sustainment options in distributed environments.¹⁵⁴ Additionally, investigating force

signature management of engineer equipment to satisfy force reconnaissance and counter-reconnaissance needs must occur to mitigate unintentionally revealing the disposition of troops.¹⁵⁵ Mastering multi-variable market research practices are also warranted to leverage commercial technologies better.¹⁵⁶ This implies that a broader array of water production equipment should be made available for informed equipment sourcing to meet the needs of distributed forces.

Compared to current capabilities, commercial capabilities must be investigated to explore emerging water harvesting technologies, such as atmospheric water generation, that may optimize engineering strategies and fill capability gaps in small-scale water sustainment. Specifically, this research addressed how engineers can diversify water production options with air-to-water technologies to provide drinking water to distributed forces. Results sought to answer the research question: “How can Marine Corps Engineers most effectively provide water to distributed forces in austere environments?” And indicated that diversification of provider and water production capabilities might be a viable way forward to offer more options for water resilience at austere locations. An in-depth review of all alternatives is recommended to make all options available to the warfighter. The below chart summarizes key issues and implications.

Issue	Implication
AWG incapable of producing water in all environments	-Diversify water capabilities with a wider array of purification equipment -Diversify employment concepts with a ‘layered’ approach -Sustain RO capabilities and competencies -Monitor emerging metal-organic framework and desalination technologies
RO inadequately scaled to be effective for new concepts	-Employ AWG technologies -Investigate alternative water solutions such as passive water harvesting, host nation infrastructure, commercial foraging, low-pressure RO filtration, tradecraft, etc. -Enhance and leverage joint, interagency, intergovernmental, and multinational services, and support and rehearse water conservation techniques
(cont)	

Issue	Implication
Water Treatment Equipment is too heavy for dismounted troop sustainment and requires too many additional resources	-Employ AWG on autonomous and light tactical vehicles -Monitor DARPA atmospheric water extraction developments -Explore low-pressure water filtration options -Develop field-craft skills for water survival -Establish global water infrastructure and equipment common operating picture -Conduct pre-conflict theater shaping (i.e., cache equipment and packaged water, host nation water infrastructure development, water reconnaissance repository) -Investigate water equipment's capacity for interoperability and multi-capable performance (e.g., multi-power source, water dispensing modes, combining RO and AWG capabilities)
Equipment is not suited to create water on the move	-Integrate multi-functional AWG systems into mobile platforms -Investigate power and water storage and distribution options for modular alternatives that may be configured to mobility platforms
Geographic dispersion can complicate standardizing water approaches because of disparity in climates	-Invest in multi-capable equipment to diversify water support equipment -Combine RO and AWG technologies as a 'system of systems' that is modular and can undergo multiple configurations -Invest in engineer water reconnaissance activities to better define an environment and inform planning requirement determination -Conduct additional research on the implications and impacts of distributed operations on small-scale sustainment
Preparing for new concepts and range of military operations is complex	-Investigate artificial intelligence, equipment sensor, and modeling for intelligent control of water-making assets -Investigate simulation technologies for predictive logistics and more precise water estimations
The requirement to conduct DMO and the range of military operations causes issues in scaling and selecting equipment	-Integrate power and water harvesting technologies in RO equipment -Create a multi-variable commercial off-the-shelf purchase framework -Conduct research to make water equipment more abundant by incorporating water production technology with common-use equipment (e.g., generators, power storage sets, tactical vehicles, trailers, etc.) -Investigate the use of computer-assisted and artificial intelligent systems for asset management, control, and engineer assessment
Centralized hub-and-spoke sustainment undermines new concepts	-Diversify water production, storage, distribution, and engineer reconnaissance assessment options -Utilize prepositioning and cache options for water equipment and supply -Sustain traditional concepts for water resilience and assurance that is to be accompanied by understanding interdependencies of logistic networks and infrastructure in the given environment
Water treatment equipment creates signature management concerns	-Conduct water equipment EMS/IR signature assessment to clarify mitigation measures -Investigate low/no power water filtration options (i.e., pneumatic low-pressure filtration) -Identify and develop cover and concealment options -Investigate sub-terrain concealment options

	-Exercise water conservation and offset equipment operational times for short duration water production practices -Explore options of tactical employment as a deception tool
Water treatment requires special skills	-Investigate cross training and multicapable skill development -Investigate sensor and intelligent equipment technologies for remote asset management and control options -Explore smart-display technologies for ‘any user’ operations and instruction assistance -Habitually align or permanently assign water technicians to maneuver units to advise, assist, accompany, and enable tactical water support
Inland operations, signature management, and security concerns limit raw water source site selection	-Employ AWG to preserve ‘water anywhere’ and ‘on the move’ water production capability -Diversify water production capabilities for wider array of options to include foraging and harvesting strategies -Invest in theater shaping through engineer reconnaissance and establish geospatial repository -Explore small scale water distribution and storage options -Investigate use of aerial, space, and unmanned platform image analysis tools to locate water sources -Develop skills and invest in partner infrastructure development for establishing wells, prepositioning water harvesting equipment,
Water security is too important to risk in a distributed context	-Sustain bulk water competencies and explore distributed logistics concepts -Explore littoral and logistic connector sustainment platforms to leverage added ‘layer’ of water security -Invest in multi-purpose and multi-source water making equipment

Table 8. Summary Findings. Summary of the author’s observations and findings.

This research limited scope to atmospheric water generation. It did not thoroughly evaluate water support alternatives like contracting, interservice support, foraging, field tradecraft, field fabrication or composition, autonomous delivery systems, or other commercial technologies like photovoltaic ultraviolet purification or desalination technologies. While these considerations were beyond the scope of this research, they too may increase the capacity to provide potable water to dispersed troops. As research indicates that diversifying water treatment can improve unit self-sustainment, other water purification processes may contribute to broadening the range of capabilities in a distributed environment.

Additionally, the criterion and metrics selected did not rigorously review cost, fuel consumption, power demand, signature management practices, and many other factors that deserve a thorough review. This research may facilitate a more profound discussion regarding such topics to assist in reconceptualizing water operations and inform future investment considerations in a period increasingly defined by environmental security and operational uncertainty, with water typically among the significant concerns of a growing crisis. These considerations must undergo a thorough formal study to assess impacts on water operations and alternative water treatment solutions supporting distributed operations.

This study synthesizes emerging Marine Corps operating concepts' impacts on tactical water operations and presents atmospheric water generation to sustain disaggregated forces more effectively without local infrastructure. Accepting that future force engagement cannot assume tactical or regional military superiority, conducting logistics from centralized distribution hubs to maintain troops efficiently becomes highly degraded. Operating in contested areas demands concealment in every regard that relies on the ability to move independently.

At least to some degree, atmospheric water generation can provide essential water sustainment for distributed troops to enhance their abilities to move more freely. Although imperfect due to dependency on climate and the need for a supplemental mobility platform, atmospheric water generation breaks tethers to geographical features and lessens the burden on logistic chains, thereby promoting autonomy. Said another way, atmospheric water generation is a viable alternative conducive to distributed operating concepts in specific circumstances and must be exploited. The result enables a commander to distribute forces more widely with water security and increases the difficulty for opposing forces to predict and locate friendly troops in the distributed environment.

Recommendations

Considering the results found in this study, the following recommendations and actions are provided to inform future implementation.

- Integrate water treatment and atmospheric water generation technologies into existing mobile platforms. While cost was not evaluated, the author assumes some cost-benefit may be considered with bundling new equipment designs that integrate water treatment.
 - Integrate atmospheric water generation with combat mobility, engineering, and logistic platforms. Common small-unit equipment items like ultra-light tactical vehicles, off-road trailers, combat vehicles, autonomous logistic movers, and mission essential equipment like generators or traditional water treatment would improve the versatility of the equipment.
 - Program management offices for engineer equipment must seek to expand current equipment with multi-functional equipment sets to perform various sustainment functions that may increase options closest to the point of need.
- Monitor DARPA's development of advanced technologies like sorbent, and metal-organic frameworks (MOF), which demonstrate the potential to draw water from the atmosphere in very low humidity environments. Experimentation, regardless of the maturity of the science, is encouraged to unveil limitations in MOF lifecycles and the quality of water to confirm or deny the feasibility of future applications in austere locations.
- Sustain medium and heavy reverse osmosis equipment sets and explore storage and distribution methodologies. Water security is too important to chance sustainment on

first-layer logistics. In-depth employment concepts must be developed to understand how second-layer logistics can resolve potential water shortages for troops operating within weapons engagement zones.

- Redundancy in plans must account for intermediary base capabilities and prepare for expanding operations beyond stand-in force concepts.
 - Distributed operations must include the range of military operations in planning and preparing to employ traditional bulk water operations.
- Pursue component coordination to share resources and broaden understanding of sister service capabilities and gaps. Army, Coast Guard, Navy, and Air Force are undergoing similar transformations that acknowledge problems with access and placement in peer competition, suggesting small and efficient force presentations as a solution. For example, the Army has modulated profiles for expeditionary close-combat Brigade Combat Teams. The Coast Guard elevated joint contributions under the *Maritime Trident of Forces* much to the same end. Navy composite warfare constructs feature flexible forces cross-functionally organized to align Strike Group sensors and shooters against threats. And the Air Force opted to invest in “small, remotely located...elements” for Air Expeditionary Task Forces “...to execute operational tasking when there is not an existing Air Force structure prepared to accept expeditionary forces.”¹⁵⁷ The collective change suggests that military components acknowledge the operating environment as an extended battlespace that is too dynamic for conventional employment and should synchronize collective requirements at the joint level.
 - In particular, the Marine Corps and Air Force have common stakes in a strategy that calls for small, highly agile, and rapidly deployable forces to gain and

maintain access to areas that complicate opponent decision-making abilities. As the Air Force has implemented Gyrene Mangrove power and water harvesting, close coordination at the tactical level should be mirrored at the institutional level to increase corporate knowledge of the advantages, restraints, and interservice training opportunities.

- Explore radar, imagery analysis, and heat scattering technologies to facilitate the camouflage of water equipment and sites. Stealth is an inherent quality of clandestine operations, and new technologies must be pursued to consider all signature management practices. An assessment of engineer equipment signatures should be investigated to identify the types of signatures equipment generates and recommend mitigation measures to avoid detection.
- Pursue tactical sustainment wargaming to identify the most suitable locations and scale of equipment assignment. Water harvesting dependence on environmental conditions suggests that equipment is only ideal for some areas; therefore, aligning atmospheric water generators to regions with suitable climates is advised.
 - A thorough analysis of regions, times, and conditions where atmospheric water generators can provide adequate quantities of water may also aid in prepositioning equipment and making them available for in-theater training ahead of occasions where access or transportation may be more difficult.
- The Marine Corps Joint Water Resources Management Action Group representative is recommended to propose developing joint methods for incorporating environmental conditions into operational calculus to express water security risks better. This implies that all service engineers should commit to joint intelligence preparation of the operating

environment (JIPOE) before employing distributed maritime operation constructs. JIPOE for water can facilitate emerging concepts by defining circumstances and factors to determine better a given environment's operational capacity and limitations. Additional topics for action-group consideration are:

- Developing computer-assisted processing, storing, and dissemination of data can share information throughout the joint force to the benefit of the total force and inform more precise water sustainment data and must be explored to modernize asset management, contribute to more intelligent control of resources, and facilitate planning to enhance sustainment decision making.
- Investigate engineer reconnaissance and shaping functions regarding water infrastructure and support operations. The complex nature of developing water support makes predicting water demand in distributed environments extremely subjective to dependent highly relative environmental factors and broadly varying operational needs of the force in question. This suggests that engineers may be well suited to shaping the operating environment by contributing to the preparation of the environment.
- Because research indicates that diversifying water solutions promotes sustainment in a distributed operating environment, consider synthesizing joint capability for early shaping activities such as host nation market research, alignment of theater asset overviews, coordinating temporary commercial or interservice or partner force equipment loans, investigating host nation or operational area geological features and activities; evaluating the feasibility of accessing existing water infrastructure; vetting of tactical force's water demand requirements; monitoring

water consumption rates and developing predictive logistics models; and dedicating reach back-reach forward coordination teams for asset management.

- Invest in a joint force water infrastructure and resource management data archive.
A military approach that capitalizes on disaggregated stand-in forces can complicate military water support beyond average human capacity.
- Investigate pairing a joint water management archive with intelligence, reconnaissance, and surveillance equipment to include air and space geospatial analysis technology for determining all water sources. As the most suitable equipment requires an open water source, engineers could be benefited from other technologies that identify available water sources before conducting ground reconnaissance. Reconnaissance drones, satellite imagery analysis, and other geospatial intelligence collection technologies may increase awareness to better inform and tailor water support strategies for appropriate equipment selection.
- Commit resources and funding to water sustainment simulations, modeling, and artificial intelligence programs better to manage the complexity of sustainment in distributed environments.
- Integrate artificial intelligence for forecasting water demand, equipment visibility, and quality control. Additionally, artificial intelligence can match appropriate equipment types for troop missions—deconflicting availability and remote monitoring systems for maintenance, condition, location, etc. Significant effort should be made to ensure software compatibility of sensors and ‘smart’ hardware.
- Develop interdisciplinary skills in non-engineer personnel to operate water treatment sets and assume sustainment tasks. Distributed operations conducted at a large scale will

stress the availability of water technicians. Creating incidental operators may provide essential skills currently exclusive to water technicians. This may provide some relief for technicians and engineers to fulfill a role in predictive logistics and support operational forces through monitoring systems and facilitating the balancing of multiple water sources. That is appropriate to the schemes of maneuver but will have to rely on non-engineers and communication networks to reasonably manage water resources in distributed environments.

- Develop an open purchase framework for selecting commercial off-the-shelf equipment to simplify open purchase procedures and equipment selection and facilitate requirement determination for any user. Acquisition channels allow a great deal of flexibility but are often limited by a need for more ability to frame and articulate a requirement. In the case of tactical water production systems, specifying the parameters needed to support a requirement may be overwhelming for ordinary users and delay acquisition processes. Therefore, a conceptual framework or computer application designed to guide any user through specifying requirements and match with a vetted equipment pool may be beneficial. Results indicate that favorable outcomes follow a diversity of equipment, but limiting options to existing inventories may stress equipment pools that the commercial market can fulfill. Distributed operations will require a significant amount of tactical water production equipment that the national industrial base may only be capable of satisfying through commercial options. Early requirement shaping may provide insights into understanding the demand and capacity that commercial equipment may help with early coordination.

- Conduct an in-depth comparison of feasible alternatives for small-scale water, including contracting, interservice and multinational support, commercial low-pressure filtration systems, foraging and fabrication of filtration systems, field tradecraft, and passive water harvesting. This comparison should include atmospheric water generation, low-pressure filtration systems, and desalination technologies to ensure all opportunities are explored and would complement the findings from this study.
- Tri-service review of water consumption planning factors should consider refining demand calculations. More precise measurements of daily water demand may be calculated by researching the relationship between human needs, perspiration, and waste in various environments against energy exerted. With technology developments that can more precisely monitor water intake and perspiration, a more definite scope of consumption can be made. Though human physiology has not changed, our understanding of it has and with access to human energy monitoring systems. Predictive algorithmic models may contribute to water conservation techniques or facilitate managing water needs in the battlespace in a manageable fashion.
 - Adjusting water requirement calculations that assume factors of medical, vehicle maintenance, or other non-consumable reasons should be evaluated as a reduction in unit size infers a decrease in peripheral water needs. As broad calculations drove doctrine and water planning factors for larger formations, redundancy factors, consumer rates, and peripheral water demand need updated measures. An in-depth study and review to revisit data that can calculate water demand by body types, physical activity levels, region, etc., may more precisely calculate troop needs to reduce unnecessary redundancy or waste.

Tentative Marine Corps guidance and literature on alternative water sources suggest atmospheric water generation is viable though somewhat limited means to provide water to distributed forces in austere environments. Research results show that diversifying water solutions can optimize essential sustainment for troops. Atmospheric water generation can improve the operational reach of very small and mobile units while preserving a clandestine profile, but it requires special considerations. Additionally, this research provides a point of departure to facilitate the development of a future concept of employment that is likely to include a wide variety of water support solutions to distributed forces and enhance the effectiveness of engineers throughout the force. Lastly, this study provides assumptions and estimations from which further discussion can generate to help shape water requirements in a distributed environment and inform engineers of existing opportunities for water support in the future.

APPENDIX

System	Physical Attributes			Value Range 1=least desirable 5=most desirable
	Size	Weight in pounds	Notes	
TWPS¹	35'x 75' work area 240"x96"x96" or 1,280 ft ³	9,552 lbs.	Bladders, hoses, and pumps create sizeable footprint	1
LWPS²	75'x 100 work area Modular components equivalent to 78"x48"x37" or 80.2 ft ³	912 lbs.	Components are modular for hand carry, and is sling-load capable	3
PWPS³	Composed of main and accessory cases each sized at 31.6"x23"x19.5"	2 cases at ~130 lbs. each Total=250	Set of cases can be reduced to one for operations	4
SWPS⁴	Sized for backpack carry, dimensions unavailable	Fresh=8.5 lbs. Brackish =26.7 lbs.	components separable	5
Mangrove⁵	20"x24"x24"/module or 3.8 ft ³	3 modules at 150 lbs. each Total=450	Can be scaled to integrate on mobile platform	3

Appendix A 1. Physical Attributes of Water Systems, Weighted Values. Sources annotated in Appendix notes.

¹ *Tactical Water Purification System Specifications Sheet*, Marine Corps Systems Command, <https://www.marcorsyscom.marines.mil/Portals/105/PfM/LCES/ES/Bulk%20Fuel%20and%20Water%20Systems/Bulk%20Water%20Systems/Info%20Sheets/PURIFICATIONSYSTEMWATERTACTICALTWPS.pdf?ver=2018-11-06-084827-487>.

² Technical Manual (TM) 11720A-OI, *Operation and Maintenance Manual with Repair Parts List for Light Water Purification System*, Headquarters Department of the Navy, July 2011.

³ TM 13308A-14/1, *Operator and Field Maintenance Manual for Platoon Water Purification System Model 0500134*, Engineer Systems Program Management Office, 2 February 2021.

⁴ Marine Corps Systems Command, Program Management Office, "Squad Water Purification System Concept of Employment and Capability Overview" (working brief, 22 September 2022) provided to the author in correspondence 30 January 2023.

⁵ Gyrene Mangrove Specifications Sheet, version 3, provided to the author courtesy of Gyrene Engineering Management (chief operations officer, Gyrene) 14 October 2022.

System	Signature				Measures of Concealment	Difficulty to Conceal	*Mobile	Value Range 1=least desirable 5=most desirable
	*EM/IR	Heat	Noise	Smell				
TWPS¹	Yes	Med-high	High	Yes	Camouflage, Deception	Significant	Low	1
LWPS²	Yes	Low-Med.	Med.	Yes	Camouflage, Mobility	Moderate	Med.	3
PWPS³	Yes	Low	low	None	Stowe, Mobility	Ideal-Moderate	Med.-High	4
SWPS⁴	No	None	None	None	Stowe on persons	Ideal	High	5
Mangrove⁵	Yes	Low-Med.	Low	None	Camouflage, Mobility	Moderate	Med.-High	4

EM = Electromagnetic IR = Infrared

*EM Signature analysis was not conducted. The presence of EM/IR is assumed with electronic and/or mechanical oscillation of equipment, components, or peripheral equipment (e.g., vehicle or generator).

Appendix A 2. Water System Stealth Attributes, Weighted Values. Sources annotated in Appendix notes.

¹ *Tactical Water Purification System Specifications Sheet*, Marine Corps Systems Command, <https://www.marcorsyscom.marines.mil/Portals/105/PfM/LCES/ES/Bulk%20Fuel%20and%20Water%20Systems/Bulk%20Water%20Systems/Info%20Sheets/PURIFICATIONSYSTEMWATERTACTICALTWPS.pdf?ver=2018-11-06-084827-487>.

² Technical Manual (TM) 11720A-OI, *Operation and Maintenance Manual with Repair Parts List for Light Water Purification System*, Headquarters Department of the Navy, July 2011.

³ TM 13308A-14/1, *Operator and Field Maintenance Manual for Platoon Water Purification System Model 0500134*, Engineer Systems Program Management Office, 2 February 2021.

⁴ Marine Corps Systems Command, Program Management Office, “Squad Water Purification System Concept of Employment and Capability Overview” (working brief, 22 September 2022) provided to the author in correspondence 30 January 2023.

⁵ Gyrene Mangrove Specifications Sheet, version 3, provided to the author courtesy of Gyrene Engineering Management (chief operations officer, Gyrene) 14 October 202

System	Source Water				Rate of Production	****Time 1 Day Water Supply	Able to Scale up/down	Value Range 1=least desirable 5=most desirable
	Fresh	Brackish	Salt	Air				
TWPS ¹	X	X	X	-	(F) 1,500GPH	1.5 min.	No	2
					(S) 1,200 GPH	1.7 min.		
*LWPS ²	X	X	X	-	Lg. 400/800 GPH	5.5/2.25min.	Yes	5
					Med. 135/235 GPH	16/9.2 min.		
					Sm. 75/125 GPH	28.8/17.3min.		
PWPS ³	X	X	X	-	(F)18 GPH	2 hr.	No	3
					(S) 22 GPH	1.63 hr.		
**SWPS ⁴	X	X	-	-	(F) 80 oz/min	1.04 hr.	No	3
					(B) 60 oz/min	1.28 hr.		
Mangrove ⁵	X	X	X	X	(F) 17 GPH	2.11 hr.	Yes	4
					(S) 17 GPH	2.11 hr.		
					*** (A) 1.2 GPH	30 hr.		
F=Fresh B=Brackish S=Salt A=Air *LWPS Large (Lg.), Medium (Med.), and Small (Sm.) configurations reflect salt/freshwater production rates **SWPS is undergoing testing. Rates assume the unit is unaffected by continuous use. ***Assumes 80-degree temperature and 60% Relative Humidity ****1 day of supply calculated for a (12) man team at 3 gallons per day per person (36gallons)								

Appendix A 3. Water Systems Economy of Scale Comparison with Weighted Values. *Note: Palatability and water quality are not included due to insufficient data and numerous variables associated with source water. Criterion-weighted value assessed in terms of versatility and efficiency. Sources annotated in Appendix notes.*

¹ *Tactical Water Purification System Specifications Sheet*, Marine Corps Systems Command, <https://www.marcorsyscom.marines.mil/Portals/105/PfM/LCES/ES/Bulk%20Fuel%20and%20Water%20Systems/Bulk%20Water%20Systems/Info%20Sheets/PURIFICATIONSYSTEMWATERTACTICALTWPS.pdf?ver=2018-11-06-084827-487>.

² Technical Manual (TM) 11720A-OI, *Operation and Maintenance Manual with Repair Parts List for Light Water Purification System*, Headquarters Department of the Navy, July 2011.

³ TM 13308A-14/1, *Operator and Field Maintenance Manual for Platoon Water Purification System Model 0500134*, Engineer Systems Program Management Office, 2 February 2021.

⁴ Marine Corps Systems Command, Program Management Office, “Squad Water Purification System Concept of Employment and Capability Overview” (working brief, 22 September 2022) provided to the author in correspondence 30 January 2023.

⁵ Gyrene Mangrove Specifications Sheet, version 3, provided to the author courtesy of Gyrene Engineering Management (chief operations officer, Gyrene) 14 October 2022.

Resource Dependence	System				
	TWPS ¹	LWPS ²	PWPS ³	SWPS ⁴	Mangrove ⁵
Surface Feature	Yes	Yes	Yes	Yes	No
Manpower	>2	>2	1	1	1
Skill	Medium-High	Medium	Low	Low/no skill	Low
Maintenance	High	Moderate	Low	-	Low
Material Handling	Required	Recommended	2xMan lift	None	Vehicle integrated
Secondary Containment	Required	Required	Dispenses to user	Dispenses to user	Internal – Dispenses to user
Supplies	Routine resupply	Routine Resupply	Filters	Filters	Filters
Power Source	Generator	Pump	Battery (multi-source)	Hand-powered (Pneumatic)	Battery (multi-source)
Value Range 1=least desirable 5=most desirable	1	3	4	5	5

Appendix A 4. Water Systems Resource Dependency Comparison Chart with Weighted Values. Sources annotated in Appendix notes.

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