BIO-INSPIRED WATER SYSTEMS: COASTAL FOG AS A SEASONAL WATER RESOURCE FOR NORTHERN CALIFORNIA

by

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Water supply and demand presents an immense challenge for communities around the world. The future impacts of climate change and population growth are expected to intensify global water stress as freshwaters become more scarce and human competition over weakened water resources increases. Our society needs to adapt our current water supply system to our changing environment in the same way that organisms have adapted over the course of Earth's history to survive various environmental stressors. Taking inspiration from nature– using biomimicry– we can devise more efficient ways of collecting and using water resources.

The development and use of fog-capturing nets around the world exemplifies the benefits of biomimicry. Communities around the world have utilized fog to meet their water needs. Taking lessons from these projects, this paper investigates the viability of fog as a community water resource, in addition to exploring if and how fog nets could be implemented in California to help mitigate the state's water stress.

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Table of Contents

List of Figures

Introduction

The future of our planet is uncertain. Climate change and population growth pose a great threat to both the health of humans and the natural resources on which we depend. Our freshwater resources are particularly susceptible to these threats. Water scarcity and competition over water resources are projected to intensify as our global population grows and climate change continues to alter the quantity and quality of our freshwater ecosystems. Consequently, there is an increasing need for innovative and sustainable solutions to combat these issues. Taking inspiration from nature (referred to as 'Biomimicry') is a useful tool for confronting and solving issues in human design. Fog-capturing nets are an example of biomimicry in action– modeling contraptions after fog-catching organisms in order to provide water to communities facing water scarcity and drought.

Many small, rural communities around the world have already utilized fog nets to satisfy their water needs. This paper will examine the costs and benefits of fog water supply systems in order to answer the question: is fog a viable water resource for communities? If so, under what conditions are fog nets most effective and efficient? More specifically, this study seeks to determine whether or not fog nets could be a practical, sustainable solution to California's current and intensifying water stress. This paper also draws from a few different organizations to provide general guidelines for implementing a fog net system.

Chapter 1: Water, Climate Change, and Population Growth

Water is an essential resource for most life on Earth. Freshwater sources, or non-salty waters, such as lakes, rivers, and glacial melt, are especially important for maintaining life on our planet. As a critical component of the hydrological cycle, freshwater keeps ecosystems in balance and helps to maintain a habitable planet for all forms of life. For many species, including humans, freshwater is our only source of drinking water and thus, we are dependent on its abundance and quality to ensure our health and survival (Kernan et al., 2010).

That being said, most of our water is extracted and used for other purposes. Agricultural and industrial production requires copious amounts of water. For reference, producing one cup of coffee uses 140 L of water and producing one kilogram of beef requires 1,600 L of water (Schemenauer et al., 2017). These levels of water usage are concerning because freshwater is extremely scarce. Freshwater makes up less than 3% of Earth's total water resources and covers under 1% of the Earth's surface (Woodward et al., 2010). Moreover, this small fraction of water is divided up to satisfy over seven billion humans, as well as countless other plant and animal species. Thus, freshwater supply and demand presents an immense challenge for communities around the world.

This challenge is exacerbated by two factors: climate change and population growth. While climate change will affect water resources in different ways around the world, a few major impacts will be broadly felt. First, climate change is projected to increase both the frequency and intensity of droughts in many regions of the world, thus reducing the supply of freshwater and increasing competition over these depleted water resources. Warming temperatures will also cause water loss through increased rates of evaporation, as well as through decreased mountain snowpack, which will put stress on other freshwater systems, such as rivers downstream. In addition, rising sea levels pose a threat, as saltwater will encroach on bodies of freshwater. Overall, climate change will transform freshwater quantity, quality, and functioning (Woodward et al., 2010).

In addition, freshwater issues will intensify with population growth. Some growth projections have estimated that the number of people on the planet will reach around ten billion by mid-century (McDonald et al., 2011). As a result, there will be greater competition over resources, including water for drinking, agriculture, and other daily uses. According to estimates from the United Nations, around two thirds of the world's population will be impacted by water scarcity by the year 2025 (Mayerhofer & Loster, 2015). Figure 1 demonstrates the widespread impact of water stress worldwide, projected for the year 2040.

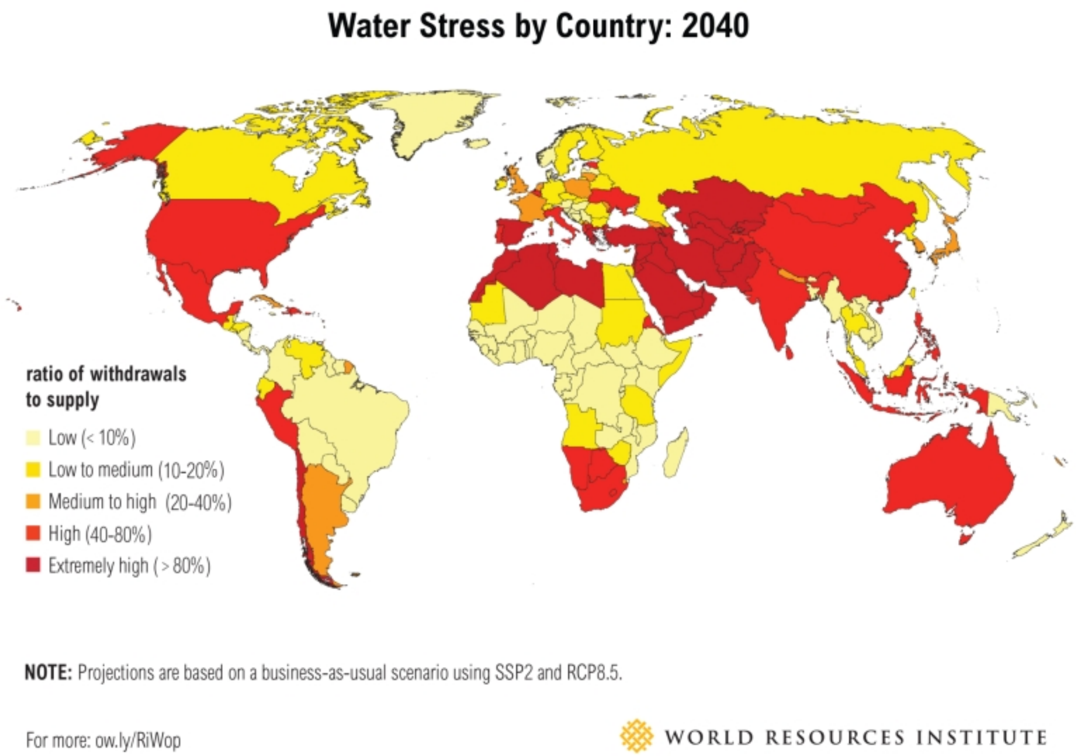

Figure 1: Projected Global Water Stress by 2040

This map illustrates water stress (ratio of water withdrawal to available water supply) projections by country for the year 2040. Yellow and orange indicate low to medium water stress, while areas shaded in red indicate high water stress (Luo et al., 2015).

In the United States, water stress will be (and has already been) felt in the western states and most notably, in California. The western US has already experienced longer frost-free seasons, earlier snowmelts, and decreases in snowpack. While precipitation has increased in the Pacific Northwest, rainfall has decreased in the southwest, with states like California experiencing longer and more severe drought events. Climate change is expected to exacerbate water supply issues in this region, causing greater freshwater shortages. Water demand is also projected to rise with population growth, potentially leading to over-allocation of limited water supplies

(Dettinger et al., 2010). Figure 2 illustrates the severity of the water issues felt by the western US.

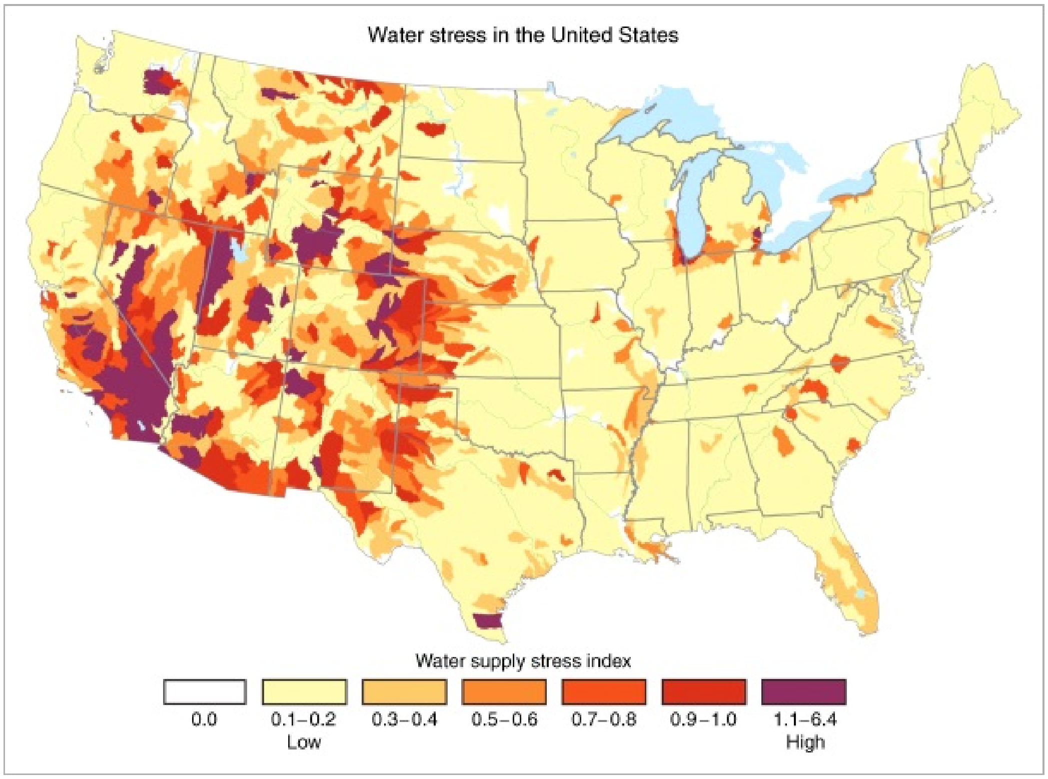

Figure 2: Water Stress in the United States

This map illustrates current water stress (ratio of water withdrawals relative to the available water supply) in the United States. Water demand exceeding 40% of available water supply (or a ratio of 0.4 or higher) indicates high water stress (Dettinger et al., 2010).

With the projected increases in water scarcity and water stress, there is increasing pressure to find alternative solutions for our impending water crisis. Some different water catchment and management techniques are already being practiced in drought-stricken regions, including wastewater treatment, groundwater storage, and desalination plants. Despite helping preserve our freshwater resources, some of these methods are quite expensive and energy-intensive (Hanak & Lund, 2012). Therefore, we need to explore more creative, innovative, and efficient ways of capturing and storing water in both urban and rural communities. We need to adapt our water systems to address the future challenges with climate change and population growth in order to build more resilient and sustainable communities.

Chapter 2: Biomimetic Solutions

Because natural systems are resilient and sustainable, they provide strong models for urban systems. Since the beginning of life on Earth, organisms have evolved and undergone many adaptations in order to survive and prosper on this ever-changing planet. Plant and animal species have developed unique and impressive ways of tolerating and enduring even the most severe of environmental stressors. For this reason, there are many lessons we can take from nature when it comes to addressing human adaptation and the evolution of urban spaces. In *Biomimicry in Architecture,* architect Michael Pawlyn writes, "For virtually every problem that we currently face– whether it is producing energy, finding fresh water or manufacturing benign materials– there will be numerous examples in nature that we can benefit from studying."

This statement holds especially true for finding sustainable solutions and adapting to climate change. Nature is an ideal model for sustainability because Earth's organisms and ecosystems are extremely efficient. Plants and animals are sensible beings– they are conservative when it comes to using resources, meaning they limit waste. They utilize what is available and abundant in their local environments and spend their time and energy wisely. Therefore, human communities can look to nature as a model for creating sustainable and resilient infrastructure and design.

The process of mimicking the function or form of biological organisms is commonly referred to as biomimicry or bio-inspired design. Biomimicry is the practice of emulating nature's principles, as opposed to sustainable development methods like biophilic design or bio-utilization, which directly integrate plants and other living things into the urban environment. This particular practice of design has been utilized throughout human history, helping to inform various disciplines and fields of study, including transportation, architecture, engineering, and product design, to name a few. While mimicking nature is not a recent concept, the term biomimicry was not coined until the 1960s and became popular in the 1980s (Pawlyn, 2011). Biologist Janine Benyus and architect Michael Pawlyn have been pivotal in this popularization by propagating the ingenuity and promise of biomimicry. Some examples of biomimicry include plant burrs inspiring the invention of Velcro or modeling building ventilation techniques after temperature-regulating termite mounds.

For human communities facing the challenges of water scarcity and climate change, biomimicry can help inform innovative and sustainable solutions. There are many organisms in nature that are exceptional at collecting and storing water to meet their needs. Desert plants and animals are especially efficient and inventive at capturing and storing water because they have such limited access to water. Desert species have adapted unique and effective ways to quench their thirst and survive year-round drought conditions. With little rainfall and standing bodies of freshwater, many species have evolved to utilize the only consistent source of water in their habitat: fog.

Surviving in one of the driest habitats on Earth, the Namib Desert Beetle (*Stenocara gracilipes*) is one desert species that relies exclusively on fog as its source of water. Every morning, this tiny beetle climbs up the coastal sand dunes to harvest the fog that forms overnight as a result of the coastal currents and wind patterns (Norgaard & Dacke, 2010). It does so by positioning itself in a headstand– angling its head toward the ground with its back facing the wind. Due to the combination of hydrophilic and hydrophobic surfaces[1] on the beetle's back, fog droplets are able to stick to water-attracting bumps and accumulate until gravity forces them to roll down the waxy, water-repelling valleys into the beetle's mouth, as is demonstrated in Figures 3 and 4 (Guadarrama-Cetina et al., 2014). In this way, tiny fog droplets can sustain the life of this small organism.

Figure 3: Namib Desert Beetle in Fog-stand Position (Domen et al., 2013)

[1] Hydrophilic and hydrophobic surfaces are defined by the contact angle of a water droplet to a surface. A hydrophilic surface has a contact angle of less than degrees, whereas a hydrophobic surface's contact angle is greater than 90 degrees. Thus, water will spread on a hydrophilic surface and droplets will bead on a hydrophobic surface (Yuan & Lee, 2013).

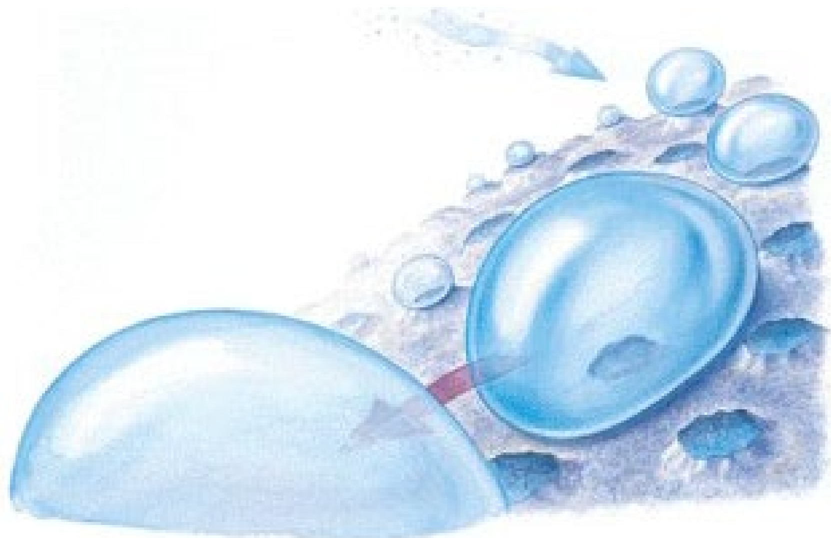

Figure 4: Beetle Elytra

This image above depicts a zoomed in view of fog droplets attaching to the hydrophilic bumps on the beetle's elytra (wings) and rolling down the hydrophobic valleys toward its mouth (Roberto Osti)

Desert species are not the only life forms that capture fog for water. Fog is also utilized at a larger scale as a water resource for coastal forest ecosystems. Similar to the Namib Desert Beetle, conifer needles can collect fog from the air due their hydrophilic and hydrophobic surfaces, as well as their comb-like leaf structure (Goodman, 1985). While coastal forests cannot and do not rely explicitly on fog to meet their water needs, this additional resource is important for replenishing these ecosystems in times of water stress or drought (Carbone et al., 2013). For example, in conifer forests along the coast of northern California, fog drip acts as more of a seasonal water resource, providing much needed moisture during the region's otherwise dry summers (Fischer et al., 2016). In fact, for California's redwood forests, fog drip accounts for 40% of the forest's summer water intake and 34% of its water over the course of a year (Domen et al., 2014). While the fog-collecting trees themselves do not rely much on fog as a water source, the plants in the understory benefit greatly from the fog dripping down from the canopy. On average, understory plants receive over 65% of their yearly water supply from fog drip, with some species relying solely on fog as a water resource (Dawson et al., 1998). In addition to acting as a water source for forests, fog drip can also provide nutrition to the ecosystem because fog droplets carry dissolved gases and other nutrients that are beneficial to the soil and plant growth (Azevedo et al., 1974).

Looking at these cases of fog catchment from a biomimicry standpoint, it is interesting to consider if and how humans could utilize fog as a water resource. In areas around the world with daily abundances of fog, exploring bio-inspired fog catchment presents a sustainable and innovative solution to water scarcity and climate change related issues. In studying human-scale fog collecting mechanisms, we may be able to lessen the stress on other water resources and better prepare for drought conditions and climate change.

Chapter 3: Fog Nets

Fog Collection: An Overview

Collecting fog for human use is by no means a new practice. There is evidence that many civilizations around the world utilized fog to satisfy or supplement their water needs. In Chile's Atacama desert, communities assembled piles of stones for fog to cool and condense on, capturing the resulting droplets in various devices under the rocks. In another arid region of the world, ancient Palestinians planted vegetation along honeycomb panels to aid with irrigation. Populations in Oman and the Canary Islands also used fog as a resource, placing buckets underneath trees to capture droplets coming off the leaves or needles (Fessehaye et al., 2014). Thus, over the past centuries, humans have taken inspiration from nature to devise innovative ways of utilizing their available water resources.

In more recent times, various organizations and designers have explored the possibilities for utilizing fog as a water source, taking inspiration from fog-collecting organisms and ecosystems, such as the Namib desert beetle and coastal redwood forests. For example, Warka Water Inc., an American nonprofit organization, implemented a tower designed to capture fog from the air to provide an alternative water resource for a small Ethiopian village. Designer Kitae Pak also took inspiration from the fog-capturing abilities of the desert beetle to create the "Dew Bank Bottle." Mimicking the shape and surfaces of the beetle, this water bottle is designed to fill with water overnight as the fog rolls in.

The most notable among these innovative fog-capturing devices is the fog net. Fog nets, like the Dew Bank Bottle and Warka Water Tower, can capture fog droplets from the wind. Built with plastic mesh, these large sail-like nets have been set up in arid regions that receive steady amounts of fog daily. To maximize their water yield, these fog nets are most commonly installed at high elevations along coastlines. As the wind blows fog and low-lying clouds inland through the mesh pores, droplets attach and accumulate on the triangular mesh surface through impaction. As the droplets combine and grow larger, the weight and gravitational forces cause them to roll down the net. The fog droplets are collected below the net by a tray that funnels the water to pipes and tanks, where it is stored and then transferred to communities for various purposes, including drinking, irrigation, and reforestation (Klemm, 2012). This system has been utilized as a local, reliable, and clean source of water for communities that might otherwise lack access or proximity to freshwater resources. Figures 5 and 6 depict typical fog net set up and the materials used.

Figure 5: Fog Net

This photo shows a typical setup of two Large Fog Collectors (LFCs) side by side. These nets were used at a project site in Yemen (Schemenauer et al., 2017).

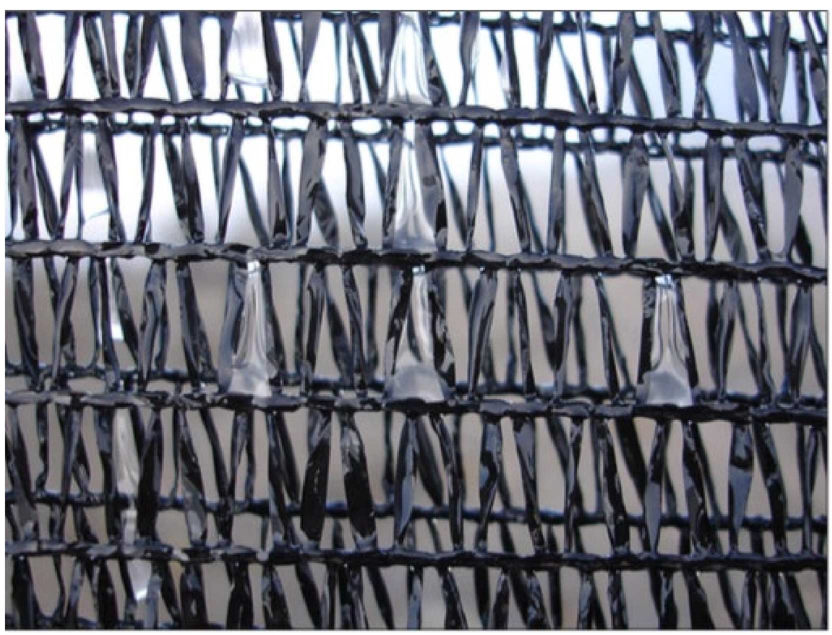

Figure 6: Raschel mesh

This photo depicts a close up view of a typical double-layered Raschel mesh used for fog collection (Schemenauer et al., 2017)

While individual fog nets can range in size, 40 square meter nets are most commonly used and on average, these large nets can accumulate up to 200 liters of water per day. Of course, the water yield differs regionally based on climatic and geographical factors (see Figure 7). However, in areas with an abundance of fog, fog nets can provide a steady and reliable source of water. Many different types of mesh have been tested, but the Raschel mesh is most commonly used for community fog net projects. The mesh is made out of a plastic material (usually polyethlylene or polypropylene) and has triangular-shaped pores (Klemm, 2012). Raschel mesh has a 35% shade coefficient, meaning 35% of its area is capable of collecting droplets. When the mesh is double layered, which is typical of most fog nets, its area has a greater shade coefficient, reaching around 50% (Domen et al, 2014). Most community fog net projects install multiple 40 square meter Raschel mesh nets, staggering them or attaching two together to maximize the amount of water they can collect.

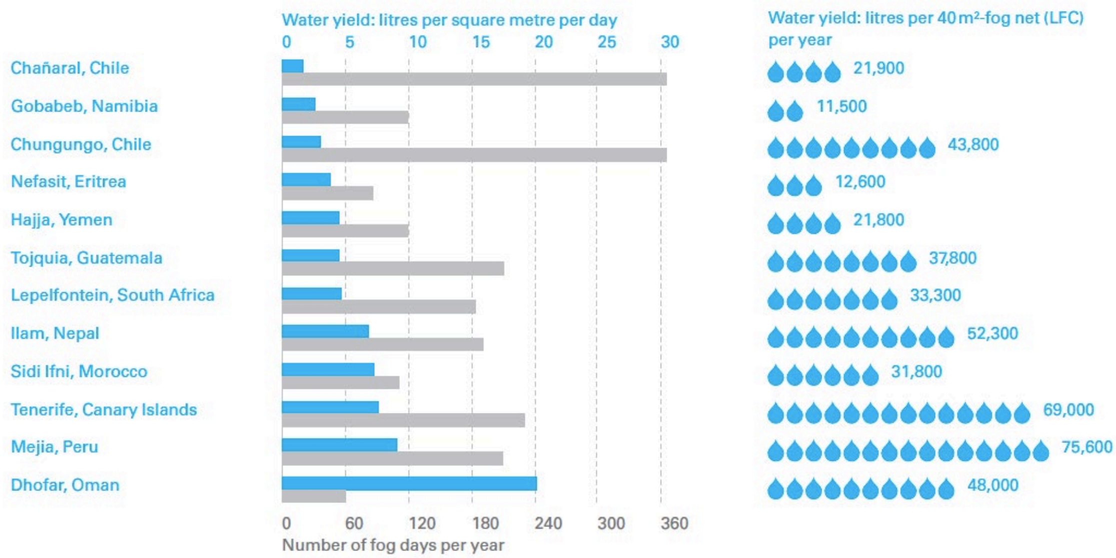

Figure 7: Water yield of Fog Nets around the world

For the graph on the left, the gray bars indicate the number of fog days experienced by a region per year. To contrast, the blue bars show the water yield for each region, measured in liters per square meter per day. The right side of the figure illustrates the water yield (in liters) of one 40 square meter fog net per year for each site (Correggiari et al., 2017)

Fog nets have been utilized around the world for almost two decades. FogQuest, a Canadian nonprofit organization, has been central to the implementation of fog nets all over the world. Founded in 2000, FogQuest has responded to the demand for clean and accessible water by poor and isolated communities with fog net installation. With support from grants, donations, membership fees, and volunteers, FogQuest has been able to aid small communities in Africa, Asia, the Middle East, and Central and South America. The organization's current project sites include Guatemala, Ethiopia, Chile, Nepal, Eritrea, and Morocco, but in the past, they have operated in Oman, Peru, Yemen, Ecuador, the Dominican Republic, Haiti, and Namibia. At these sites, FogQuest helps fund, build, and establish fog nets, in addition to training locals to sustain the projects themselves in the hopes of making a more long-lasting impact in the community.

Costs and Benefits of Fog Nets

There are many advantages to fog catchment systems. First, they are passive systems. Since they require no energy or electricity to operate, fog nets have a low environmental impact and carbon footprint. Furthermore, as fog provides a more localized water source for communities, their dependence on distant water sources is reduced. Thus, their carbon footprint is mitigated because they are not as reliant on transportation to deliver their water. Another advantage of fog nets is their long-lasting materials and limited need for maintenance. On average, the mesh nets can last up to ten years before they need to be replaced, as long as they are properly maintained. It is also fairly inexpensive to buy fog net materials and set them up. Thus, they are ideal for low-income communities.

Another benefit of fog catchment systems is the opportunities they provide for community involvement. Organizations like FogQuest often try to train locals so that they are able to gain the knowledge and skills necessary for operating and maintaining fog nets. The hope with these workshops is that locals will eventually be able to sustain these projects on their own. In this way, they can find employment or give back to their communities in a valuable way.

Despite these advantages, there are also some challenges associated with capturing fog. First, fog can be unreliable and unpredictable as a water source. Not only is there day-to-day variability, but there can also be major seasonal variation. For example, fog might be extremely abundant in the summer and then sparse during other times of the year, as is typical of Mediterranean climates. Thus, a community might not be able to rely solely on fog for water in the same way that the Namib desert beetle does year-round.

Another concern with fog nets is the sustainability of the materials used. Most types of fog mesh are made out of plastic and thus, they are not environmentally friendly. While Raschel mesh is fairly long lasting, some types of mesh are more susceptible to wear and tear with intense winds and storms and, as a result, require more upkeep and replacements. Furthermore, we do not yet understand the true ecological consequences of removing fog from local ecosystems for human benefit. The nets themselves do not take up much land and they are not tall enough to disrupt bird migration. However, capturing fog for human use might take water away from plants and ecosystems that depend on fog as a resource, such as the coastal California redwood forests. Accordingly, there is a need for more research on the environmental impact of larger scale fog net installments.

Fog Net Community Case Studies

In spite of these challenges, the following studies demonstrate the viability of fog as a resource, as well as the social and ecological benefits of community fog-catchment systems. One such project has taken place in Morocco. Located between the Sahara Desert and the Atlantic Ocean in southwest Morocco, the Berber people of Aït Baamrane experience frequent drought conditions, receiving under six inches of rainfall on average a year. In addition to experiencing water scarcity, this impoverished region suffers from water over-extraction and mismanagement, in addition to water contamination from human and animal waste, as well as agricultural runoff. Since the rural farmers depend on water for their livelihood, these water-related issues have caused people to abandon their villages in pursuit of a better life. The local water system also sheds light on the area's gender inequality. Berber women often spend up to four hours every day fetching water from the wells. Consequently, they have less time to pursue other activities, including receiving an education. In this way, water stress is very much a social issue for these people (Dodson & Bargach, 2015).

Due to these circumstances, FogQuest and a local NGO called Dar Si Hmad for Development, Education, and Culture, conducted research and eventually developed and maintained fog nets in the Aït Baamrane community. The goals for this project were to provide a clean and accessible water resource for the Berber people, as well as to relieve women and children of their energy-intensive and time-consuming water retrieval duties. After implementing and sustaining the fog nets, the organizations found that they reached these goals and increased the community's the quality of life. With fog nets, they were able to provide a sustainable water supply system that relieved women and children of their water-gathering responsibilities, allowing them the time to seek an education. Women were also trained to maintain the water systems and, in the process, they improved their technical literacy. There were also many health and ecological benefits associated with the project. In tandem with the fog nets, the community developed a water, sanitation, and hygiene program. When paired with having the clean fog water, the community experienced a lower rate of water borne illnesses. The fog nets also benefitted agriculture and the natural ecosystems by freeing up water in the wells to be used for irrigation and reforestation. Overall, the fog net installation benefitted the community socially, economically, and ecologically (Dodson & Bargach, 2015).

Another project in El Tofo, Chile demonstrates the benefits of fog net projects. In the mountainous region of Coquimbo, Chile, fog nets were considered after extensive studies on fog were conducted by the National Forestry Corp of Chile, the Federal Department of the Environment of Canada, and a couple of national research universities. In 1992, fog nets were implemented to supply water to a 300-person village whose previous water supply was delivered by truck once or twice a week. With 100 large fog nets producing 3 $L/m^2/day$ of water, the community's supply doubled to around 15,000 L/day. Thus, their supply twice-over exceeded their water demand of 14 L/capita/day. As a result, the community was able to irrigate and maintain more gardens and forest plots (Schemenauer et al., 2017). Overall, the small village benefitted from lower water costs and higher quality water (Domen et al., 2014).

Many other fog net projects around the world have demonstrated the viability of utilizing fog as a water resource for communities. These projects have been successful at sites that receive regular heavy fog, but more importantly, they have worked best within communities that are dedicated to implementing and sustaining the fog net system.

A study conducted by Fessehaye et al. (2014) on community fog use considered the factors affecting fog net project success and discovered that the social and economic aspects were just as, if not more, important than the climate and geographic factors. Projects that were unsuccessful most often lacked community involvement or local project support from government and/or non-government organizations. Fog nets failed in many communities due to net damage from a lack of maintenance attributed to a lack of training. On the other hand, fog nets were most successful in places where people had a high demand for water or strong interest in the project, as well as support from the local government and non-governmental partners (Fessehaye et al., 2014).

Chapter 4: Guidelines for Project Implementation

The following section provides a general guide for any group interested in using fog as a water resource. In order to sustain a project of this type, the guide should be tailored to fit the community where it is being implemented. This guide primarily follows FogQuest's procedures, with modifications from Munich Re Foundation and Domen et al. There are four major steps to follow when setting up and maintaining a successful fog net project. Before implementing fog nets, there must be intensive assessment and planning regarding the local climate, geography and, most importantly, the community or the beneficiaries.

1) *Assess*

The first step in initiating a fog water project is identifying where there is a community need or interest in adapting an alternative water supply system. For instance, an ideal locale would be a community experiencing issues with their current water supply. Some common issues to look for include, but are not limited to, the following: seasonal or annual water shortages, a contaminated water source, high prices for water, or long distances between the water source and its recipients (Schemenauer et al., 2017). Another possibility would be to find a community that may not have a dire need for an alternative water supply system, but that is interested in and committed to becoming more sustainable or going off the grid. Overall, it is crucial to identify a great demand or enthusiasm for such a project before moving forward with implementation.

Once a community has been identified, there should be further investigation into the community's potential for building and sustaining fog nets. FogQuest recommends conducting a survey for community members, which is provided in full in the appendix of their manual. A survey is helpful for identifying what kind of outcome the community is seeking through such a project, in addition to determining if they are committed to being involved in the building and maintenance of the fog nets throughout the process. For example, an important question to consider is do they have the time, energy, resources, and money to invest in this project? Related to this step is identifying a local partner who is committed to working with the community on the project during and after the set up. Thus, in the assessment period, it is important to communicate with local government organizations and/or nonprofit organizations, as well as potential national partners who could help fund and support the project throughout its phases (Schemenauer et al., 2017).

While the social and financial aspects are extremely important when assessing the viability of this type of project, the local climate and geography must also be considered during the pre-implementation period since fog net efficiency depends on such factors. In this phase of project planning, potential fog net sites should be assessed to determine where the most fog can be captured and easily distributed to beneficiaries. Planners should research the local wind patterns, coastal currents, fog corridors, vegetation, and mountain or slope orientation. This can be done using topographic mapping, Geographic Information Systems (GIS), and/or remote sensing (Schemenauer et al., 2017).

In general, it is important to look for mountainous areas near the coast that face prevailing winds. More specifically, planners should look for high elevation areas within 4 to 25 miles (or 7 to 40 km) of the coastline that face perpendicular to prevailing winds. Close proximity to the ocean is key due to the dissipation of fog and evaporation that occurs further inland. Open space is also important– the fewer the obstacles between the fog-carrying winds and fog nets, the better. An ideal location for nets would be somewhere in the middle of the vertical fog layer because the top and bottom layers have lower liquid content due to mixing with dry air. Accessibility is another key factor when identifying a project location. The site should be able to be accessed via roads and, if the area is sloped, it should not be too steep to allow for easy and safe building and maintenance of the nets. Land ownership and land use of the site should also be considered because some areas may not permit such types of construction (Schemenauer et al., 2017).

2) *Plan*

After assessing the local community and fog potential of an area, sources of funding should be identified or sought out. Cost estimates can be made by considering the total price of materials, in addition to the cost of labor. These estimates are highly dependent on the size and scale of the project. For reference, the cost of a Standard Fog Collector (SFC) ranges from \$100-\$300, depending on what materials are used. The mesh itself is very inexpensive, costing around \$0.25 per square meter (Schemenauer et al., 2017). One Large Fog Collector (LFC) costs on average around \$2,000 (Mayerhofer & Loster, 2015). Water storage containers costs \$100 per cubic meter. Basic system repairs are estimated to cost anywhere between \$500 to \$2500 per year based on the level of damage. In general, it is estimated that the total cost for a 200-person community project would come in around \$75,000 (Domen et al., 2014). Thus, it is important for a community to identify potential local, state, and/or federal partners as early as possible when embarking on such a project. FogQuest and other nonprofit organizations are some possible partnership types that could provide partial or full financial aid. Other options for funding include state, federal, or private grants, as well as fundraising, crowd sourcing, and venture capital.

When the necessary funding and land permits are acquired for a project, it is recommended that planners spend about a year assessing the quality and quantity of the fog water that can be utilized in the area. This step is carried out using the Standard Fog Collectors (SFCs), which are 1 meter by 1 meter fog nets. These nets can be acquired through FogQuest. SFCs are similar to their larger counter parts (LFCs) in their build and set up, as is demonstrated in figure 8. Like the LFCs, a Standard Fog Collector is made with a double layer Raschel mesh and is secured between two iron or aluminum posts. The net is set up two meters off the ground and secured to the ground using guy wires. The SFC includes a collection trough below the net that is connected to piping and a container to store the captured water. Planners should set up multiple SFCs around the site they wish to evaluate in order to determine what specific locations receive the greatest amount of fog. FogQuest recommends setting up SFCs at three or more different elevations within the site. If the site is fairly large, at least 10 SFCs should be installed (Schemenauer et al., 2017).

Once the SFCs are installed, workers should check back daily (if using 30 L storage containers) or every other day (if using 60 L containers) to see how much water is being collected, as well as to test the quality of the fog water. If the water quality does not meet the standards for drinking water, planners may want to either look into water treatment systems or consider using the fog water for other uses, such as irrigation or greywater. A rain gauge should also be installed in the ground near the fog nets in order to determine how much of the water captured by the SFCs is from rain versus fog. This data is helpful for understanding how much fog can be depended on as a water source when rain is not present (Schemenauer et al., 2017).

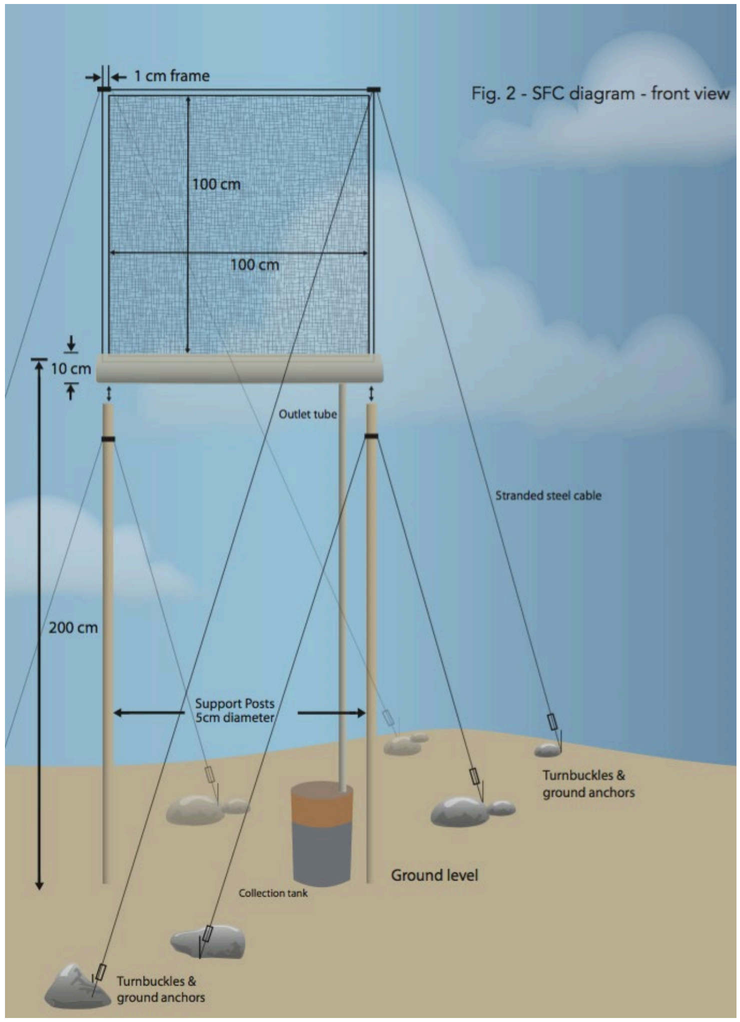

Figure 8: Standard Fog Collector (SFC)

This diagram demonstrates the size, dimensions, and setup of a standard fog collector (Schemenauer et al., 2017).

3) Implement

After assessing the quality and quantity of the fog water collected by the SFCs, the community should decide how many fog nets they see fit for meeting their needs. The number of LFCs required depends on the SFC water yield, the total site area, and the type of water usage. Planners should also consider how many fog nets can realistically be maintained by those involved in the project because they require proper upkeep in order to maximize their effectiveness and efficiency.

Once the scale of the project is decided, the nets can be installed. One LFC is constructed by stretching 40 m^2 of double-layered Raschel mesh between two posts, with the base of the mesh hoisted up two meters off the ground. The mesh is secured to the posts using cables. Cables are also used to anchor the posts to the ground with hooks. The collection trough is connected between the posts below the mesh. The trough should be connected to a piping system made up of polyvinyl chloride, high density polyethylene, and galvanized steel. The piping should be installed along the contour lines of the topography and should be buried underground in order to limit damage from animals, humans, and UV rays. The water storage container is made with stone, cement, and a plastic container. The hole in the ground above the container should be covered with a 2-3 mm plastic sheet and be sealed tightly using electric welding. Planners can decide what size container they need based on the water supply and demand. The storage reservoir should be placed at least a few meters down slope from the LFCs. In this way, water flow is forced by gravity and no pumping systems are required (Schemenauer et al. 2017). Once the system is installed, the community can decide how the water will be transported from the fog net site and allocated amongst the people. After that, fog collection can begin.

As previously mentioned, the number of nets installed should be based on the community need and available space for a project. For instance, a 200-person community needing 25 L of water per capita per day would need to install around 25 LFCs (Domen et al., 2014). Space is also important given that LFCs are large and need to be fairly spread out throughout an area. Nets can be placed side-by-side within five meters of one another or two nets can be attached. When placing nets upwind from one another, there should be at least 60 meters of space between them (Schemenauer et al., 2017).

4) *Sustain*

Following the installation and use of the fog net system, the remaining tasks include maintenance and repairs. LFCs are fairly resilient and can last up to ten years when properly cared for. The nets are subject to damage, as they can bulge and tear with strong winds. Thus, they should be regularly checked on and repaired in order to maximize their water yield. Basic tasks include patching any tears in the net, tightening the guy wires, and cleaning the mesh of any algal growth, dust, or other debris. The storage and piping system should also be routinely monitored. Once a month, the reservoir should be inspected and cleaned (Schemenauer et al., 2017). Overall, maintenance is key to the success of a project. If the community is dedicated to keeping the system in good condition, it will operate more efficiently and will last longer.

Chapter 5: The Case for California

The state of California could benefit from adopting fog net systems because of the region's frequent and severe droughts, as well as its seasonal abundance of summer fog. California has a Mediterranean climate— its summers are warm and dry and the majority of precipitation falls between the months of November and March (Carle, 2009). Droughts are not uncommon phenomena throughout the state and thus, water storage systems in the form of groundwater and reservoirs are crucial for managing and supplying water to communities during abnormally dry periods. Water transportation systems are also important, since about 75% of the state's water supply comes from north of the Sacramento area, while around 75% of the state's demand for water stems from the region south of the capital (Carle, 2009). The Bay-Delta alone provides drinking water to two-thirds of California's population, in addition to irrigating regions where 45% of the nation's produce is grown (Dettinger et al., 2015). Much of California's water supply also comes from the Sierra Nevada and the Colorado River. Accordingly, aqueducts have been installed to transfer water that has been collected in reservoirs or underground storage to cities in central and southern California (Carle, 2009).

A major threat to California's water supply is the recurring drought. As figure 9 demonstrates, California experienced widespread drought between 2012 and 2016. While the intensity of the drought has decreased in much of the state since early 2017, central and southern California are still facing high levels of drought. In 2016, it was estimated that around 87% of the state's population (approximately 33 million people) were living in drought-stricken areas (U.S. Drought Monitor, 2016). While the drought has diminished in 2017, it is likely to return in future and thus, should not be disregarded. Furthermore, with California population projections indicating a potential growth of up to 60 million people by 2050, demand for water will increase immensely throughout the state, placing more strain on the already fragile water resources and management systems (Hanak & Lund, 2012).

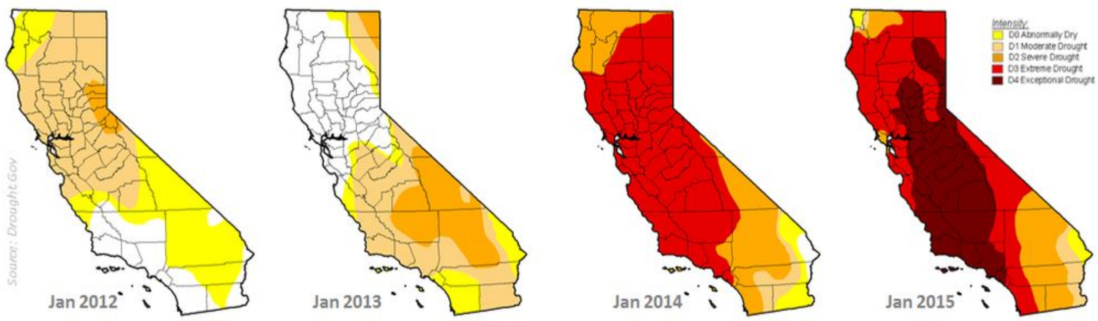

Figure 9: Map of California Drought

These maps depict the level of drought experienced throughout the state of California during the month of January from 2012 to 2015. The darker the red, the more severe the drought (U.S. Drought Monitor, 2012-15)

Another imminent threat to California's water supply is climate change. The state has already suffered from climate change with declines in spring runoff, groundwater, and snowpack. In the future, climate change will have diverse impacts on California's freshwater resources. Some major changes will include shifts in seasonal timing of runoff and snowmelt, increases in evapotranspiration, and longer and more severe droughts. Groundwater, an important water resource, may also decline as aquifer recharge from snowmelt decreases. Wetland habitats will also be altered with sea-level rise changing water composition from fresh to saltier waters. Encroaching sea waters may also cause an increase in invasive species, which can drive out native plants and animals that are important for maintaining aquatic ecosystem health (Dettinger, 2015).

These effects of climate change, combined with population growth, will be extremely taxing on California's water supply.

In light of these challenges, California is in need of inventive and sustainable water management solutions. Utilizing fog presents a potential solution to California's intensifying water stress. To date, there have been no community fog net projects in California or the United States. However, fog nets have been used for other endeavors. On Santa Rosa Island, off the coast of Santa Barbara, fog collectors have been used for a reforestation project. By creating fog drip system with the fog nets, they hope to regrow forests that can then sustain themselves with natural fog drip (U.S. National Park Service, 2016). Elsewhere in the state, fog nets have been used in the production of alcohol. In the San Francisco Bay, Hangar One vodka company created a limited release of "Fog Point Vodka" made with water accumulated from fog nets (Steinmetz, 2016).

Aside from these instances, fog has mostly been a topic of research in California, specifically through the Pacific Coastal Fog Project. Laboratories throughout the state have collaborated with NOAA and USGS on research to better understand fog patterns due to the ecological importance of fog. Researchers at California State University at Monterey and University of California Santa Cruz have tested fog water volume and mercury content using fog nets (Torregrosa et al., 2014). In addition to this research, the Pacific Coastal Fog Project compiled ten years of fog data. Figure 10 represents summer abundance of fog and low cloud cover (FLCC) along the northern California Coast between 1999 and 2009, recorded using Geostationary Operational Environmental Satellite images (GOES) (Torregrosa et al., 2016).

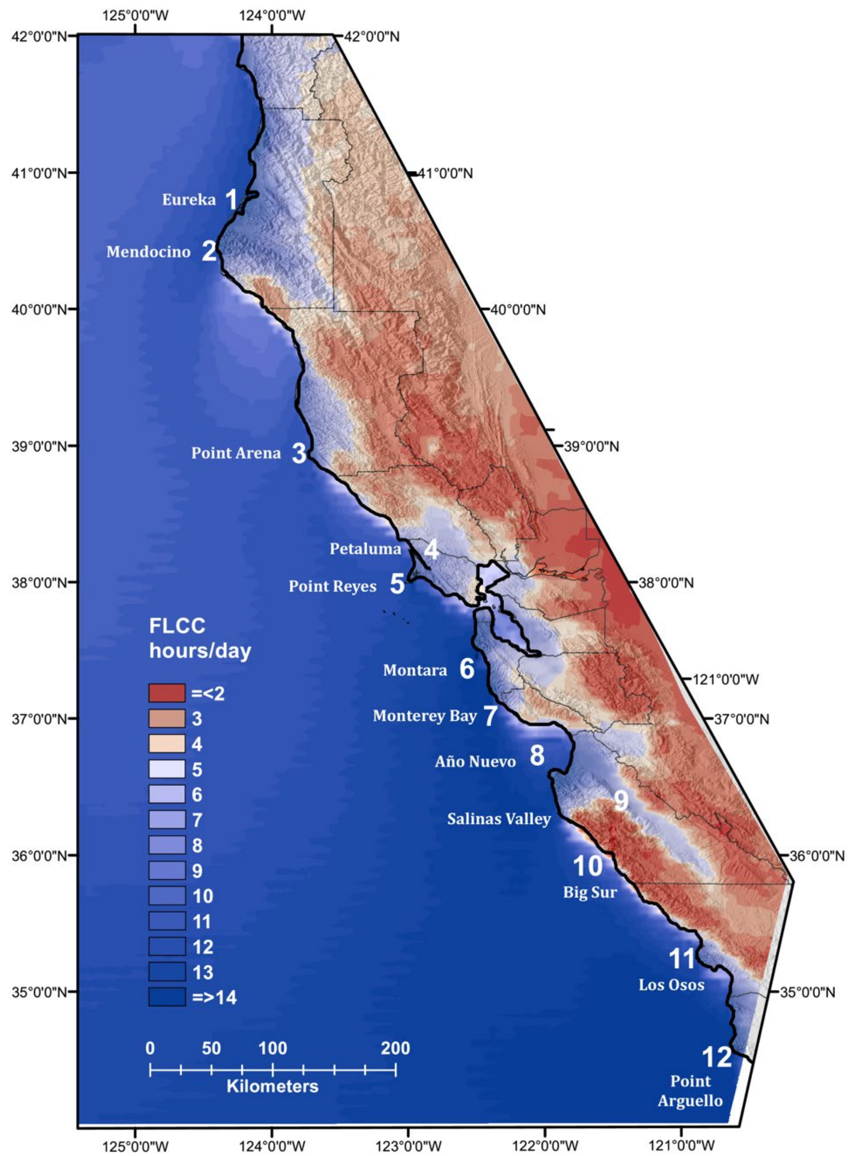

Figure 10: Map of Northern California Fog and Low Cloud Cover

This map demonstrates the number of hours of fog and low cloud cover (FLCC) experienced by coastal towns in northern California. Areas shaded in red receive few hours of FLCC and areas represented in blue receive more hours of FLCC. This data was collected between 1999-2009 at the following locations: 1) Eureka/Humboldt Bay, 2) Cape Mendocino, 3) Point Arena, 4) Petaluma Gap, 5) Point Reyes, 6) Montara/Half Moon Bay, 7) Año Nuevo, 8) Monterey Bay, 9) Salinas Valley, 10) Big Sur Coast, 11) Los Osos Peninsula, 12) Point Arguello (Torregrosa et al., 2016)

This data reveals the potential for successful implementation and use of fog nets along the northern California coast due the region's summer abundance of fog. As a result of the high pressures system and cold ocean upwelling from the prevailing northwest winds, there is a marine layer of fog that comes inland overnight and in the early mornings throughout the summer (Torregrosa et al., 2016). Between June and October, the northern California coast experiences around 40-44% fog frequency, whereas coastal regions of southern California sustain a fog frequency of approximately 24% (Domen et al., 2014). For this reason, fog nets would be more effective and work more efficiently along the northern coast, rather than in southern California. Based on the FLCC map, the regions mapped in varying shades of blue could be great places for fog net utilization due to their high frequency of fog and low-lying clouds throughout the day. Of the ten study sites along the coast, the city of Montara in the Half Moon Bay area (south of San Francisco) has the highest presence of fog and low-lying clouds, with an average of 14 hours of FLCC per day (Torregrosa et al., 2014). Thus, this region would be ideal for exploring fog net potential.

While fog nets have been used around the world to satisfy the water needs of small communities, it might be preferable to take a different approach to fog utilization in northern California. First, water collected from fog along the coast of California may not be potable because of the potential pollutants in the air from nearby industries and populated cities. The water collected at FogQuest sites has met World Health Organization's drinking water standards, but these locations are usually in remote regions of developing countries. Since fog can carry mercury and other metals, water might need to be treated before being consumed by residents living in or near often polluted, urban areas (Domen et al., 2014). Otherwise, without treatment, water from fog nets could be used in California for other purposes, including irrigation, greywater, and reforestation projects.

Another factor to consider is the scale of the project. Since fog nets have been used primarily in communities with under 500 residents, it has been possible to meet and even exceed an entire community's water demand. In northern California, fog water yields may not be high enough (or consistent enough) to supply water to an entire community. Instead, fog nets might function better as a supplementary water supply. Fog nets could also be utilized for smaller groups within a community. In this way, a neighborhood, a school, or a small business might be able to meet most or all of their water needs with fog nets.

A study of fog collection in Big Sur, California demonstrates the potential water yields of fog nets in the area. Over the course of two summers in the Big Sur area, Hiatt et al. (2012) used SFCs to determine how much fog makes landfall every day. Upon completing their data collection, they discovered that on average, the SFCs collected around 3 $L/m^2/day$. This amount does not account for rainwater collection. Thus, a fog net in this area would likely produce higher water yields when taking into account other forms of precipitation (Hiatt et al., 2012). With an SFC only covering 1 square meter of space, we can estimate that an LFC installed in the same area would collect a daily average of 120 L per day. To put these amounts into the context of California's water demand, it is estimated that the average water usage along the central California coast is 413 L/capita/day (Domen et al., 2014). Thus, multiple large fog nets would need to be installed to meet one household's total water demand. However, one large fog net could provide one household with drinking water. One LFC could also irrigate a plot of land ranging in size from 100 to 300 m^2. Therefore, one fog net is capable of supplying enough water to be used for household gardening, small scale agriculture, or a small natural restoration site.

That being said, Big Sur is not a region with especially high fog frequency based Pacific Coastal Fog Project's FLCC map. And yet, if that area could still utilize fog at a small scale, it is tempting to explore the possibilities of fog harvesting further north, closer to the San Francisco and Half Moon bays. With Montara averaging 14 hours of fog a day throughout its summers, fog nets might be able to provide greater amounts of water to communities in that area. Montara is a small town, with a population of 2,903 covering an area of only 3.9 square miles (U.S. Census Bureau, 2015). The average water demand in this hydrologic region of California is lower than that of the central coast, with a residential usage of around 390 L/capita/day (California Department of Water Resources et al., 2010). Assuming fog nets would produce a higher water yield in this region than in Big Sur, one fog net would be able to satisfy a greater percentage of a household's water needs or it could irrigate a larger plot of land.

Overall, due to the high water demand in California and the seasonality of fog abundance, fog nets would be best utilized along the northern California coast as a supplementary and seasonal water source for community use. With such high water usage in the San Francisco Bay Area and along the central California coast, fog nets would not be able to provide enough water to meet an entire community's needs. That being said, a fog water system could still be implemented throughout the region as a supplemental water resource. In small towns like Montara, a fog net system could provide households with water for irrigation or greywater. With average household water usage in the area falling under 400 L/capita/day, one large fog net could provide a residence with around one-third of their daily supply. Thus, a site with ten or more fog nets could supplement a small neighborhood's water supply. Another option includes using a multiple-net site to satisfy the water needs of a school, park, or small business. Fog water could even be harvested and set aside for specified uses, such as irrigating a community garden site or restoring forested areas. While these ventures are small in scale, they could make a significant impact in California by offsetting water extraction from other sources and freeing up resources to be used by communities in other parts of the state that are experiencing more immediate or dire water needs.

Though a California fog net system would start out small in scale, ongoing research on fog collection shows promise for the creation of larger scale and more efficient and effective fog-harvesting systems in the future. Rajaram et al. (2016) tested different mesh coatings and discovered that the mesh was 50% more efficient than generic Raschel mesh when it was covered in a superhydrophobic coating. They also discovered that reducing the size of the mesh pores enhanced fog collection. The Munich Re Foundation has also been testing nets with different geometrical designs, concluding that the classic Raschel mesh was not the most effective at fog catchment (Mayerhofer & Loster, 2015). Other research groups have considered different shapes and sizes of fog nets in improving fog-harvesting efficiency. For example, with strips of mesh attached diagonally between the double-layered Raschel mesh, the "Eiffel" collector was able to collect ten times the amount of water than a regular LFC (Domen et al., 2014). Thus, with such levels of research on fog harvesting, new technologies may emerge in the future that make fog water systems more effective, efficient, and capable of being utilized at a larger scale.

While advancements in technology can improve fog-harvesting efficiency, the social aspect of fog net projects is key to project success, as has been demonstrated in communities around the world. For fog nets to work effectively in California, they would need to be implemented within communities that are motivated and willing to help build and maintain their fog water system. As Fessehaye et al. (2014) concluded in their research of fog net project success, local partnerships and strong community commitment can make or break a fog net system. While climate and geography are important factors for fog catchment, if there is a lack of support for or dedication to a fog net project, the fog net system will be ineffective. Overall, a project on the northern California coast will be most efficient and beneficial within a dedicated and properly-trained community that is supported by local governmental or non-governmental partners.

Conclusion

Imagining a World with Fog

Walking along the coastline, large nets are visible up in the mountains. They look like sails in the wind, as they capture water from the air and deliver it to the local community downslope. The fog net site resembles the likes of alternative energy plants, such as solar and wind farms, with the nets concentrated in a confined area. The idea behind them is similar too: utilizing resources that are locally abundant.

In this sustainable coastal town south of the San Francisco Bay area, fog catchment has its own place in natural resources management and the municipal water supply system. Fog nets have provided for the locals– job opportunities, education, and of course, an alternative and sustainable water supply. These people are connected to their water resources and the ecology of their hometown because their water supply system is so localized. As a result, they are more conscious of their water supply and usage. They use the summer fog as a seasonal, supplementary water resource during the dry season, lowering their demand for water from reservoirs and rivers, which are needed in other parts of the state. They use the fog to sustain their community gardens, to reforest their coastal ecosystems, and some households recycle it as greywater. No matter the use, this fog net community is resilient and adaptable.

From the Past and into the Future

With the past success of fog net projects across the globe, it is difficult not to imagine how these systems could be implemented in the United States, and specifically, in California. With the state having already suffered long and severe droughts, it is important to consider implementing alternative and more sustainable water supply systems. As climate change continues to threaten freshwater resources and population growth projections indicate increased completion over said resources, California communities should prepare themselves for scenarios of high water stress in the future. While fog nets may not be able to perform in the same way as they have in small, rural villages, they could nonetheless be an effective tactic for lessening the strain on other freshwater sources, especially during periods of drought.

Upon reviewing fog net case studies and research on fog collection, I conclude that coastal fog can provide a viable water resource for small, rural communities. Fog nets could also be utilized at many northern California communities as a supplementary, seasonal water supply system. Based on average per capita water use in the region, fog nets would not be able to fully meet a household's water needs. That being said, fog water could supplement conventional water resources in a community, providing a local resource that could be used for irrigation, greywater, or restoration of natural areas. In this way, extraction of other freshwater resources could be reduced during critical demand periods such as the state's normally dry summers or through periods of drought. Projects like the Santa Rosa Island reforestation program and Hangar One's limited fog vodka release exemplify the diversity of fog-water use and the potential for fog net adoption in the state in the future. Considering the ongoing research and potential for advancements in fog net technology, there is a bright future for fog harvesting.

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