WATER SUPPLY & CLIMATE CHANGE:
THE IMPACT OF WATER STRESS ON
FIRE PROTECTION SYSTEMS

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Abstract: Many fire protection systems rely almost entirely on having an adequate water supply to aid in control or suppression of fire. Furthermore, local fire departments also rely on the water supply as a part of their response. If water sources are somehow lost or the supply infrastructure is damaged, the protection system will not work as intended and thus the reliability of suppression systems heavily depends on adequate water supply. This project focuses on how fire protection system design and water supply system design must begin to include the concept of climate change, specifically water scarcity or stress, to the discussion of reliability of systems.
This project conducts a detailed literature review of current water supply practices, design of suppression systems that depend upon the use of water supplies, and the impacts of water stress or scarcity on water supply systems, as well as a gap analysis of what areas need to be researched more from the lens of fire protection systems and climate change. Additionally, the report will include four case studies including: the 2021 Texas, USA Arctic Blast water crisis, 2018 Cape Town, South Africa 'Day Zero' water crisis, Spain's freshwater resource loss, and Australia's water crisis. By studying these scenarios, the project provides a vast look from rural to urban areas (including the wildland urban interface), as well as differing climates, and varying reasons leading to the water stress or scarcities in the regions. A final source of data is a stakeholder survey focused on plans for and experiences with water shortages.

It is determined that various stakeholders should be involved in the communities planning for a water supply shortage, policies should be developed to help upgrade infrastructure to combat possible shortages, and alternative means of water supply should be considered such as the use of desalination plants to help supplement existing water supplies.

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CHAPTER I

INTRODUCTION

Many fire protection systems rely almost entirely on having an adequate water supply to aid in control or suppression of fire. Furthermore, local fire departments also rely on the water supply as a part of their response. These water supply systems are vast underground networks of pipes connected to a source of water. If that source of water is somehow lost or those pipes are damaged, the protection system will not work as intended. Typically, in rural areas, there will only be one source of water in small communities, and they may not have the resources available to quickly fix any supply issues. If these areas experience some form of climate change, even something such as a drought, they may not have adequate water supply for their fire protection systems to function. Figure 1 shows predicted water stress projections worldwide for 2040. Climate change and water stress is typically focused on domestic, agricultural, and industrial uses. Fire protection systems are not usually an area of consideration in the context of climate change. As such, this research is an important area to explore to ensure that codes, standards, and public policy have time to change.

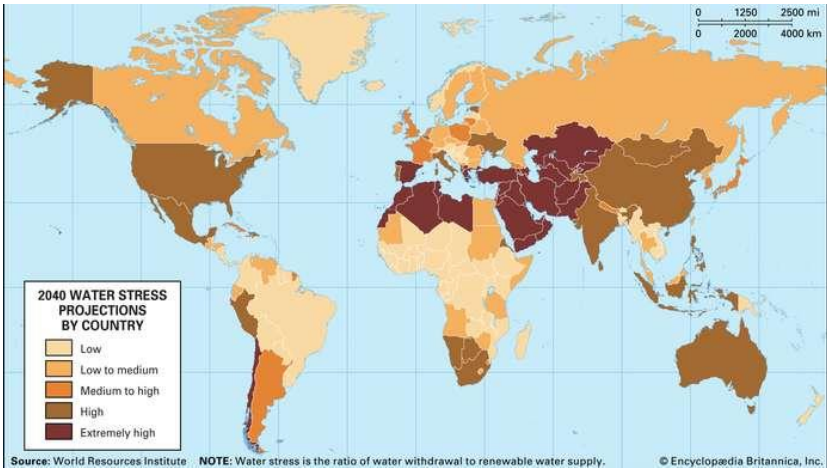

Figure 1. Water Stress Projections (Petruzzello, 2021)

Fire protection systems are typically designed based on the available water supply of an area. Generally, the first thing done on any fire protection project that involves an active fire protection system is getting the water supply information. This information can be gathered by hand (physically performing a flow test) or if in a sufficiently urbanized area, a computer model is used to determine average supply. After gathering the supply information, the system is designed to work based on that water supply and NFPA 13 Standard for the Installation of Sprinkler Systems (in most cases). This water supply and NFPA 13 are then used to determine exactly how much pressure and how many gallons per minute a single sprinkler needs to suppress a fire. If that water supply is incorrect, the system may not be adequate to perform its intended function. If that water supply changes over time, be it for any reason (the source has changed, the piping array has been reconfigured, or if the area is experiencing a water shortage), then this supply information is invalid, and the fire protection system will not work as designed. The system could either perform inadequately or fail. System inadequacy is one that is not being enough, and a failure is an omission of performance (Merriam-Webster, 2022).

Both a system failure and inadequacy will result in similar detriments to water-based fire protection systems and the property it protects.

Water is one of the most precious resources on earth. Not only is it required for human survival, it is also generally used it to put out most fires. Water supply issues are usually one of the very core necessities to any population. These sources can be springs, wells, lakes, rivers, or in some cases the ocean. In many municipalities, these sources are also supplemented using water towers for storage purposes. These water towers usually hold massive amounts of water for high demand periods as well as in times of emergency. These towers are also used to take advantage of hydrostatic pressure and are typically 30+ feet tall. Building these towers this tall ensures that even if the city loses power in an emergency, the pressure of the water being up so high will force flow downwards and continue providing water to the municipality for some time.

Using these sources, people are provided with fresh water, and fire protection systems are also provided with enough water to adequately perform as designed. If the water source dries up, such as a lake, or is in the case of a river, diverted, these municipalities will have no water until they find another solution. Without water, the area will not be able to support the people that live there, and the fire protection systems will also be out of commission. If a drought happens, or something else affects the supply, there could be repercussions to the fire protection systems. Therefore, it is our intention to gain an understanding of the potential size and scale of these repercussions through this research.

Around the world, the climate is continuing to change and affect how fire protection engineers and designers plan for the built environment. Climate change is defined as a change in global or regional climate patterns over the long-term (NASA, n.d.). According to NASA (n.d.), climate change indicators have included land and ocean temperature increases, ice melt from glaciers, rising sea levels, and the frequency and severity of extreme weather. Extreme weather can include heatwaves, wildfires, droughts, hurricanes, and polar vortexes. These extreme weather events can lead to water supply issues for domestic, agricultural, industrial, and fire protection use.

Many times, fire protection systems are designed based upon a single location and point in time from a water supply test. Meaning, on a given day at a certain time, the water flow test provided this much flow and pressure at a location. Fire protection design may not always take into account the nuances of weather events' impact on fire protection systems (O'Connor, 2020). Fire protection design, water supply, and climate change all need to be considered in the design of systems for the built environment as well as tactical decisions for responding firefighters. If the construction on a large project lasts multiple years or if there is a modification to the building that requires a change to the fire protection system after construction has finished, there may be changes in the water supply. Furthermore, communities, from rural to urban, need to keep up with the growth and water needs of the community to ensure the infrastructure can continue to support the demands. The water supply information the system was originally designed upon may have changed radically since the building was built. This can significantly impact the performance of said system and in some cases the system may not even be adequate for the building based solely on a new water supply.

This research seeks to explore what literature exists on water supply systems, particularly as they relate to changes due to climate and the impact to fire protection systems. Additionally, this research will discuss the gaps within the literature. A survey was conducted to understand perspectives of identified stakeholders regarding water supply systems, climate change, and fire protection system impacts.

CHAPTER II

LITERATURE REVIEW

Water supply systems are a crucial component to most fire protection systems. This review will cover the importance of water supply systems, the various types of these systems, and how these systems interact with fire protection systems. The implications of climate change on how water supply systems are affected will also be reviewed. Studying these effects on water supply systems and how in turn those effects impact fire protection systems, will give researchers a new perspective on how to account for these changes in the design of infrastructure.

Fire protection systems are defined by the NFPA Glossary of Terms as "Any fire alarm device or system or fire extinguishing device or system, or their combination, that is designed and installed for detecting, controlling, or extinguishing a fire or otherwise alerting occupants, or the fire department, or both, that a fire has occurred" (NFPA, 2021). For the purposes of this study, the focus will not be on alarm devices, but only on fire extinguishing systems, and only those systems that use water as a primary extinguishing agent. This study aims to explore the effects of water supply changes on fire protection systems. If these systems do not have access to water, they will not be able to function. This study will be looking at sprinkler systems, standpipes, water spray systems, water mist systems, and foam-water systems.

Water based fire protection systems, as the name implies, use water to suppress or extinguish a fire. The means of delivering water will depend on the specific system. In most applications, the use of a sprinkler system is the most basic of the water-based fire protection systems. NFPA 13, the Standard for the Installation of Sprinkler Systems, states “purpose of this standard shall be to provide a reasonable degree of protection for life and property from fire” (NFPA, 2022b). Sprinkler systems work by a configuration of piping connected to a water supply with outlets consisting of sprinkler heads with elements that are activated by heat. Once these elements have been activated, water flows through the outlet and discharges by hitting the sprinkler head to suppress the fire emergency. These systems are used in a variety of applications, ranging from commercial and industrial systems to those used in residential use.

While the design of the sprinkler systems may vary vastly in different occupancies, the purpose and the need for water will remain the same. Regardless of use, the system will require access to water. Residential occupancies can have slightly different systems. The use of sprinker systems in domestic occupancies, i.e. one and two family dwelling units, is covered in NFPA 13D. These are systems designed for use in homes, and while they still require water to function, they can slightly divert from the need for a constant water supply through the use of water tanks. These tanks still need to be filled at the inception of the system and when/if the system discharges the tank will need to be refilled (NFPA, 2022a). Use of sprinkler systems in residential occupancies, hotels and apartments, four stories or less, is governed by NFPA 13R (NFPA, 2022c).

Automatic sprinkler systems pressure and flow requirements are typically determined by the hazard class of the building the systems are installed in. Sprinkler systems are designed to NFPA 13 standards which give modifiers based on square footage and design density, so at the lowest possible requirement, a system will need at least 150 gallons per minute of water pressure to function effectively. The pressure requirements as stated above are at the minimum of 7 pounds per square inch per head (NFPA, 2022b). This can make systems vary in pressure and flow requirements greatly.

There are a variety of other fire protection systems besides sprinkler systems that actively use and require a water supply system. Standpipes and hose systems are typically used in tandem with another fire protection system, like sprinklers. Standpipe and hose systems are governed by the NFPA 14 Standard for the Installation of Standpipe and Hose Systems (NFPA, 2019). Standpipes and hose systems are generally used as a supplement to help firefighters with water suppression and extinguishment. They are connected to the fire department connection on the side of a building and can be used for additional water supply in tandem with fire trucks. This means they usually require an active water supply, and if that water supply was not available, firefighters would typically have a much more difficult time in firefighting efforts. Firefighters typically can use a quick calculation used by the National Fire Academy to estimate the required flow to suppress a fire. This formula is typically length times width, then divided by three for an approximate number in gallons per minute that would be required to suppress a fire (Academy, 2019).

Another fire protection system that requires the use of water is a water spray system. Water spray systems are similar to sprinkler systems but with some key differences. The pressure in these systems is much higher and the discharge of a fire spray system is usually much larger than a typical sprinkler system as there are multiple discharge outlets as opposed to the singular sprinkler discharging. Per NFPA 15: Standard for Water Spray Fixed Systems for Fire Protection these systems are typically used for much higher hazard areas than sprinkler systems, including hazards such as: gaseous and liquid flammable materials, electrical hazards, and vapor mitigation (NFPA, 2022d). These hazards are widespread, especially electrical hazards, and the use of water spray systems is necessary as a typically sprinkler system used on an electrical hazard will only make the hazard greater. Water spray systems require much more water than other fire protection systems. According to NFPA 15, the most hydraulically remote nozzle shall not be allowed to drop below 50 pounds per square inch during nozzle operation (NFPA, 2022d).

The use of water-based fire protection systems, such as sprinklers, are typically only seen in areas of the world that are highly developed. Developing countries do not necessarily have the resources or infrastructure to support the use of water-based fire protection systems. Automatic fire protection systems require a high level of infrastructure to support their use, usually requiring a reliable water system that would provide enough pressure for the system to operate. Also, licensed and trained installers are typically needed to properly build the fire protection system. Developing countries typically must rely on manual firefighting tactics, such as water trains and the use of firefighters.

One of the major limitations of water-based fire protection systems is that they require a large amount of water. For example, the range of flow required for a sprinkler system can be from 150 gpm (light hazard occupancy at 1,500 square foot design area) to 1,000gpm (extra hazard group 2 occupancy at 2500 square foot design area). These hazard groups are defined in NFPA 13 as follows: Light hazard occupancies are where the quantity and combustibility of content is low and fires with relatively low heat release rate are expected. Ordinary hazard groups 1 and 2 are occupancies where quantities of combustibles are moderate, and stockpiles of contents are limited with moderate to high heat release rates. Extra hazard groups are areas where there is a large number of combustibles and high heat release rates are expected. (NFPA, 2022b) Water based fire protection systems commonly require anywhere from 30-120 minutes of water supply.

Water based fire protection systems also require a large amount of water pressure for the system to work, typically set forth by a minimum of 7 pounds per square inch per sprinkler head as required by NFPA 13 (NFPA, 2022b). Sometimes the existing water supply for a fire protection system does not have adequate pressure to supply the system. Additional pressure is needed to supplement the existing water pressure, which is usually achieved by using a fire pump (NFPA, 2022e). There are a multitude of different styles of pumps, but they all achieve the same outcome, usually intaking water flow with a certain pressure and raising that pressure by churning the water inside the pump. Pumps can make fire protection systems supplied by water systems with a low amount of pressure still reach the required pressure level for the fire protection system.

Another limitation of fire protection systems is the cost. The cost of a residential fire sprinkler system is around $1.35 per square foot, with the cost of commercial systems increasing to about $2.00 per square foot and higher depending on the size and scope of the system (NFSA, 2020). This cost is also upfront since the fire protection system is usually installed during the construction phase of the building. If done retroactively to add a system to an existing building, the cost can sometimes be more, as the installers may have to demolish portions of the existing structure to install the system. More intricate fire protection systems such as those requiring pumps, or a more advanced system such as a water spray or foam system, will also typically involve more upfront costs.

Once the system is installed, there are also costs that will ensue to keep the system maintained. Usually referred to as Inspections, Testing, & Maintenance (ITM), these costs will be on a yearly basis to keep the system maintained and may also be required if the system discharges. This upfront and annual cost usually sends fire protection systems to the bottom of the priority for most buildings.

This section will cover the history of water supply systems, the typical configuration of water supply systems, and the typical uses for the systems. By examining how water supply systems are configured and what they are typically used for, the implications of how a water shortage can affect the fire protection systems will be determined. The typical sources of water are generally thought of as groundwater, surface water, and ocean water. Groundwater is water found underground in the cracks and spaces in soil and rock, and typically moves through aquifers to supply surface water such as rivers and lakes (Foundation, 2020).

Water supply systems have been used throughout history. As early as the Bronze age (3200 BC), people began developing sophisticated structures to help supply water to regions that did not have direct access to lakes or rivers (Angelakis, Voudouris, & Tchobanoglous, 2020). As the development of civilization began, the larger settlements began to need more water than before. These settlements began using large reservoirs such as cisterns. Later on, as these settlements grew, new more sophisticated water supply solutions were needed (Mala-Jetmarova, Barton, & Bagirov, 2015).

The Greeks began to build the first of the more modern structures that we know as dams and aqueducts. Dams were used to cross rivers, which created a small lake that settlements used as their water supply. For settlements without direct access to rivers, aqueducts were built. Aqueducts are structures that would deliver water from a faraway source, using gravity to flow the water to wherever it was needed. These aqueducts varied in length, the largest being over 280 miles long. This aqueduct supplied the city of Constantinople and was constructed sometime around 300 BC. The Greeks also had rudimentary sanitation and purification techniques. These techniques usually involved some sort of cloth used to filter impurities out of water before it was boiled, which for its time, was highly advanced (Angelakis et al., 2020).

Water supply is a complex system involving several smaller systems working in combination. Early in the history of water supply, aqueducts were utilized to bring water from a faraway location to communities. These aqueducts were typically large concrete structures using gravity to move water across large distances. Nowadays, while aqueducts are still used to some extent, they are typically more in the form of pipelines, tunnels or canals. These systems can also still use the concept of gravity to more easily deliver water. Where gravity is not a feasible means of transporting water, pumping stations are typically used. These pumping stations use a vast amount of energy to increase water pressure. This water pressure forces enough water through these pipelines to maintain a continuous and reliable source of water to the people or systems this supply serves. Where pipelines are not used, container shipping or towing is used. This shipping can consist of tank trucks, tank ships, or other large manmade vehicles used for the shipping of water. As water is consistently very heavy at large amounts, this is a very energy intensive process (Zhaojun Wang, 2020).

Water treatment is a necessary step in the water supply process. Government agencies typically require surface and groundwater to be treated before it is allowed to be introduced into a municipal supply. This treatment process usually consists of nine steps including; collection, screening, chemical addition, coagulation and flocculation, sedimentation, filtration, disinfection, storage, and distribution (Combest, 2017). The collection process is the method of collecting the water from either a nearby surface water source, groundwater taps, by transportation, or a combination of the three. Once the water has arrived at the treatment facility, the water will first need to be screened and strained. Typically, water collected straight from the source will have large particles, and these will need to be screened out before the rest of the process can be completed. Once the water has been strained and the large materials are removed, chemicals are added to water. Some of the chemicals are used to clean the water and some are used to help the suspended particles remaining in the water clump together. Then the water is screened multiple times again to remove all of these small materials that are left in the water.

After the water has been strained and screened multiple times to filtrate all of the unnecessary materials out, the water can finally be disinfected. Usually chlorine is used to ensure all of the bacteria and microorganisms that live in the water are killed. This is a careful process as adding too much chlorine will make the water unusable. After disinfection, the water is stored. This is usually in either an underground or elevated storage tank to ensure that there will always be water supply in the case of an emergency. Then the water is distributed through underground pipelines that are served by large water pumps to ensure the water has enough pressure to reach its destination (Combest, 2017). This is usually the typical process in an urban setting, but rural water districts function similarly, albeit on a much smaller volume but over a larger area to be served.

Another recent invention for water supply systems is the presence of desalination plants. These plants take ocean water and remove the salt, hence the term desalination (Robbins, 2019). These plants can take ocean or sea water that is typically unfit for human consumption and bolster existing water supply systems by drawing from some of the largest bodies of water on earth. Desalination plants work by separating water molecules from seawater, filtering and then discharging the excess saltwater, and then treated through traditional wastewater treatment processes to ensure that the water is fit for human consumption (Authority, 2022). Using these plants can ensure that an accessible and adequate water supply is available, even when typical water supply systems can experience shortages.

The water cycle is the basic means of how water is transported around the planet. The water cycle is typically described using the three phases of water: solid, liquid, and gas. The water cycle is a very complex multifaceted system. Water evaporates into vapor and is then condensed by heat to form clouds. The clouds then produce precipitation which falls back to the earth and starts the cycle again. (Administration, 2019). This is the basic process through which all water on earth is used and reused. Humans then take the water, be it from lakes, rivers, or from groundwater itself, and then use it for our own means either for personal use or to distribute it as necessary.

Rural areas, such as agricultural areas, present their own set of problems where water supply is concerned. Rural areas have a much lower population density than urban areas. Rural areas can also be spread over a much larger land area, which can present problems when trying to supply all areas with a sufficient and adequate water supply. Rural area water supply is generally used for agricultural use including farm and livestock handling. However, it can also be used for industrial purposes when large industrial plants are located outside of urban areas. This low population density, combined with a much larger area to be served will result in large lengths of piping to be dug out and installed to serve the inhabitants and their water supply requirements.

Pmogaeva and Vasilyeva (2020) found that rural water suppliers serving villages in Russia face a multitude of problems, such as maintaining the water supply quality at a drinkable level through various means, keeping the large distribution network reliable, and disposal of wastewater. Keeping the pipeline in an adequate state is proving to be the largest challenge for Russian organizations. Inspection, testing, and maintenance of the distribution system is listed as the largest concern, as this is the only way to ensure that the network is reliable and able to provide clean, high quality water (Pomogaeva & Vasilyeva, 2020).

The network of small villages in Russia can be comparable to many other rural areas throughout the world. Water supply shortage infrastructure issues are a global issue and not just limited to a single region or country. Pundir et al (2021) conducted a risk assessment for water supplies in rural sites in Uttarakhand state, India, to look at the implementation of a water safety plan and how that plan reduces the risk to the water supply system. They took an in depth look at how rural communities can keep their water supplies safe from pathogens and keep the quality of water high enough to be considered potable. (Pundir, Singh, Singh, & Kandari, 2021). When organizations consider implementing a water safety plan, the risk to both the water supply and the distribution system is reduced considerably.

At present, some rural distribution systems use a hydraulic model to determine the network's reliability and adjust the system to provide demand where needed (Kepa, 2021). These systems are expensive and are not widely used in rural settings, but they present a very powerful tool for water supply providers to ensure the integrity of their respective systems. The use of hydraulic models, as described below, is much more prevalent in urban settings where the piping system typically serves a much smaller land area but is usually considerably more complex.

Urban regions are characterized by a large population density in a much smaller land area. Urban water supplies are used for many things, including but not limited to: domestic use, industrial uses, and general commercial use throughout an urbanized area. This leads to the water supply and distribution networks being much more complex typically than those that serve rural areas. A common system used in this type of distribution network is a hydraulic modeling system, which uses automation and information technologies to help these systems maintain and efficiently supply water to all of the area's constituents. Hydraulic modeling systems can automatically trigger pumps to divert water to different regions served by the system to account for highs and lows in the supply and demand. These systems are typically very complex and run in real time to account for the supply and demand.

One of the largest issues currently facing water supplies is the abundance of Wildland Urban Interface (WUI) fires. According to the Federal Emergency Management Agency (FEMA), the WUI is defined as “the zone of transition between occupied land and human development” ((FEMA), 2019). A main concern of WUI fires is the loss of water supply to the affected regions. If a fire removes the water supply in a region, this will inhibit both the residents in the region by lack of water and also inhibit the ability to fight the fire. Fires can remove water supplies by damaging the infrastructure of the water source, such as damaging reservoirs or tanks crucial to the water supply system. Using Monte Carlo simulations, a study simulated the WUI fires in the watershed regions in Colorado to determine the actual effect of these fires (Gannon, Wei, Thompson, Scott, & Short, 2021). It was determined that small watershed regions would not be drastically affected by these fires. Large watershed regions, however, such as the one in the Rocky Mountains that supply the majority of Colorado, could be impaired by a WUI fire. This is somewhat alarming, as this watershed provides the majority of the water used in the state of Colorado (Gannon et al., 2021). If a WUI fire were to effectively wipe out the watershed used by this state, there would be no water supply available to millions of people. The need for a secondary water source in case of incidents like a large WUI fire is becoming more necessary.

Climate change is defined by the Oxford Dictionary as “A change in global or regional climate patterns, in particular a change apparent from the mid to late 20th century onwards and attributed largely to the increased levels of atmospheric carbon dioxide produced by the use of fossil fuels". The increase in levels of carbon dioxide in the atmosphere leads to an increase in temperature. The phenomenon of climate change can have a large impact on various water supply systems/regions through various means, such as drought or other weather patterns that a region has not experienced and is not prepared for. Since the long-term effects of climate change are largely unknown, research must be done with that in mind. In this section there will be discussion on previous case studies throughout multiple regions including central North America (Illinois Watershed), Southeast Asia (Taiwan), and Mideast Asia (India). Looking at three very unassociated regions with their own distinct water supplies and climates, some broad conclusions can be drawn.

A study of the Illinois watershed, located in the Midwest of the United States, was completed to understand effects of different scenarios on the water supply (Zhang, Getahun, Mu, & Chandrasekaran, 2021). This report takes a comprehensive look at the Kankakee watershed which supplies the Kankakee, Iroquois, and Ford counties in the state of Illinois. By using a hydrological model known as the Soil and Water Assessment Tool (SWAT), the researchers developed six different water demand scenarios based on sets of different socioeconomic scenarios, using three different sets of climate change scenarios: one with high carbon emissions, one with medium, and one with low (Zhang et al., 2021). This model found that climate change would actually increase the total surface runoff of the watershed. The streamflow would reduce, but the total amount of precipitation would actually increase. This study goes on to show that the watershed region would not be greatly impacted by climate change, unless the demand for water supply was greatly increased. While there may be a lower flow in the rivers, the increase in precipitation would increase the total amount of water available to the region.

When looking at how climate change affects this watershed, an important distinction should be made between land used by humans and land that is still in its "natural" state. The impact of land use by humans will have a major effect on how the land is affected, especially in areas that have major urban development or areas cleared for farmland. *Relative Contribution of Climate Change and Anthropogenic Activities to Streamflow Alterations in Illinois,* also studies the aforementioned Illinois Watershed. A statistical analysis approach was taken to determine how both climate change and human activities have affected stream flows in the Illinois Watershed (Khan, Dahal, Jeong, Markus, & Bhattarai, 2021). This is important as much of the land in this watershed is actually used for farming of corn, which has drastically changed the landscape from its natural state. This study compares three regions that are primarily used for farmland and three regions which are still forested. Using statistical analysis, the researchers determined that the runoff from streamflow was majorly reduced once the land had been converted to farmland and that nearly no change was found in the region that was still in the forested natural state (Khan et al., 2021). The importance of this should be highlighted as while farming is not typically thought of as a major reason for reduction in water supply of a region, it can be reasonably determined that the conversion of this land to farmland by clearing the forest has resulted in a reduction in the water available in the streamflow. This could have a domino effect if this region was hit by a water supply incident, such as a drought, as the available amount of water would be majorly reduced even past what it has been already by the conversion of forest to farmland.

The next case study reviewed looks at the water availability in central Taiwan and is more focused on how climate change will affect the water supply when compared to the industrial and agricultural side (Huang, Lee, & Hong, 2021). Using a mathematical water supply model to understand how the water supply facilities will be affected by a worst-case scenario of a dry climate and how bad the issue will be, it was determined that the use of water in both industrial and agricultural industries will have a direct impact on the cost of tap water, or water used by people as opposed to businesses. This study shows how fragile the water supply system will be in a worst-case climate change scenario i.e. drought. The government of Taiwan is involved in managing the water supply systems, as the Taiwanese government wants to achieve a water supply of 20 billion cubic meters by 2031 (Huang et al., 2021).

Designing an optimal water supply portfolio for Taiwan under the impact of climate change: Case study of the Penghu area, tries to determine what specific criteria is necessary to ensure that the water supply will be able to counter the effects of climate change (Huang & Lee, 2019). The authors describe five principles: "(1) reliability of the water supply system; (2) economic feasibility—commercialized water supply technology and stable supply costs; (3) affordability of water for the public; (4) environmental friendliness—low wastewater and carbon emissions; (5) social acceptability—biodiversity conservation (provision of environmental flow)." (Huang & Lee, 2019). The reliability of the water supply is the main principle, being able to consistently rely on and use a water supply is of the utmost importance. If the water supply is unreliable to either humans or commercial activity, this will have a drastic effect on the region. By using these five principles, we can analyze each region's water supply and how much the region will be affected by possible water supply incidents/interruptions.

Many different regions began to develop their own standards on how to create a reliable water supply. As cities grew larger, the first instances of sewer systems were constructed along with the first real wastewater treatment plants. These plants typically greatly increased the hygiene in the city as water that is left untreated may contain various diseases. Around the turn of the 1900s, cities were struck by many fires, such as the great Chicago Fire. In response to these, the NFPA was formed in 1896. Out of this association we see the first of many standards relating to regulation of water supplies. In modern times, there are standards for every portion of the water supply such as, NFPA 13, 13D, 13R, 14, 15, 16, 22, 24, 25, and many others that govern the use of water from water supplies to help combat fires.

Outside of the U.S., other nations began to develop their own methods of creating a reliable water supply. Spain water management companies began growing during the early 1840s and these companies began to expand Spain's natural water supply (Pérez-de-la-Cruz, Trapote-Jaume, Melgarejo-Moreno, & Chazarra-Zapata, 2020). These companies were not very profitable, but they helped to contribute a vast amount of effort and development to the region's water supply and management. Throughout the world, many countries were trying to solve this problem of how to reliably supply cities with enough water for their greatly growing population. In recent years, these systems have become more and more sophisticated, especially in urban complexes. Systems are fed from a source, either nearby, or supplied from an evolution of an aqueduct such as a pipeline, and then usually pressurized by massive pumps and distributed throughout an entire pipeline system. As discussed earlier, hydraulic modeling systems have become more and more prevalent, leading to automation of the supply and demand for a system to reliably get water where it is needed most. This modeling software is on the cutting edge of water supply and water supply analysis.

This literature review was conducted to determine the past of water supply, the factors that can affect a water supply system, and the necessity of maintaining a water supply system. To determine the effects of stressors placed upon the water supply systems, one can begin to make conclusions on how these effected waters supply systems begin to stress the fire protection systems. Fire protection systems that rely on water supplies will also be affected by the stress water supply, and in turn will be ineffective during a fire event.

CHAPTER III

METHODOLOGY

Supplementing the literature review, the following four case studies were conducted to determine how various regions dealt with a variety of water supply shortages. The cases were spread across four continents, with a wide variety of climate conditions and water supply sources. In addition to the diverse nature of the regions, these case studies were also chosen as each case study region has had a water stressor event. By examining multiple regions of the world and their similarities and differences when reacting to water supply issues, we can determine the leading causes and effects of those shortages and the implications that such shortages have on fire protection systems.

2018 South Africa Day Zero

By early 2018, Cape Town, South Africa came very close to what was dubbed as "Day Zero", where the water supply was predicted to be shut down and residents of Cape Town would need to be rationed water daily. During a span of 3 years (2015-2017), the winters in Cape Town were extremely dry, resulting in the water storage system falling to between 15-30% of its capacity. The severe drought was conjectured to be caused by the El Nino weather pattern occurring in the region, which is where warmer ocean waters result in reduced rainfall. Between water restrictions by the government and increased rainfall in the winter of 2018, beginning in June, the water supply was able to recover to stored capacities back to 70%. However, even though this event is considered by some as 'severe and rare', understanding the geography, population, water supply configuration and usage, leading factors of shortages, and mitigation efforts will enable others to understand the impact on a region as well as what that means for those areas' fire protection systems protecting the buildings and infrastructure.

Geography and Population

Within the Western Cape province, Cape Town is the capital of South Africa. Cape Town was founded in the 1650's as a port to resupply ships. However, the location was also attractive to settlers as the farmland was fertile and well-watered. The region sits in the middle of a Mediterranean climate, where the summers are warm and dry, and the winters are wet (Axelson, 2020). Over the course of a year, the average rainfall in Cape Town is approximately 20-20.5 inches (Information, May, 30 1970). The dry period is from November to March. June is typically the wettest month.

Cape Town has an estimated population of 4.7 million people living in the city limits. This is based upon projections of growth from the 2011 census, where the population was approximately 3.7 million people. A current census project is underway now. During the drought and years leading up to Day Zero, the population ranged from approximately 4.1 million to 4.4 million ("City of Cape Town," n.d.).

Water Supply Configuration and Usage

The City of Cape Town and the South Africa National Department of Water and Sanitation oversee the water supply within Cape Town. At the time of the extended drought, the water supply in Cape Town was mainly dependent on annual rainfall filling the reservoirs. There are fourteen dams that serve Cape Town's water supply. These dams are filled from the mountain streams and rivers that are supplied from the annual rainfall. The water then is sent through pipelines through pumping stations and one of the city's 12 treatment plants and then stored in reservoirs. Approximately 30% of the water is used for agriculture and the remaining 70% of water is for urban use.

Leading Causes of Water Depletion

There are several factors that are believed to have led to the City of Cape Town having such a concern about the water supply that 'Day Zero' was looming in early 2018. During the years of 2015 – 2017, Cape Town saw a lower-than-average rainfall. In 2015, the rainfall was 80% of what is typical in the area(Wolski, August 2017). Additionally, the annual rainfall in 2017 set record lows since monitoring of rainfall began in 1933 (Wolski, August 2017). As indicated previously, the population in the Cape Town region has been exploding. There was an increase in population from 1995 to 2015 of about 70%, however, the water storage dam capacities only increased by 17% in that time period.

From a climate and geographical perspective, the area has been inundated with invasive plants that have caused water containment areas to be reduced due to how much water these plants use to survive. Furthermore, it has been indicated that there has been a temperature increase in Cape Town of approximately 1° C (1.8° F) in the last 100 years. Although that may not seem significant, more water can evaporate at higher temperatures, further reducing the water supply (Information, May, 30 1970).

Political and government decisions could also be included in causes of the water depletion, or moreover, support and solutions to provide adequate infrastructure. Dating back to 1998, policies about water resources caused tension between the political parties, which in turn led to finger pointing on the water crisis including the overall management and mitigation efforts.

Mitigation Efforts

The City of Cape Town enacted water restrictions throughout the crisis, increasing restrictions as dam water levels decreased. The level of water restrictions ranged from 1-7, where Level 7 indicated the dam levels being less than 13.5% resulting in most of the water supply being shut off and water was to be rationed. The restrictions consisted of varying approaches to reduce the overall amount of water used. It included limiting water for some urban and agricultural uses, banning non-essential use of water outdoors, encouraging the use of grey water where possible, reducing pressure in the system, and limiting the number of liters allowed per person per day ("City of Cape Town," n.d.).

There were other efforts to help push back the Day Zero date. These included plans for buying water from other reservoirs outside of the City of Cape Town system, temporary desalination plants – which were ultimately cancelled due to the cost, and water recycling. Individuals and businesses also took things into their own hands by purchasing rainwater collection tanks and drilling private boreholes to collect groundwater ("City of Cape Town," n.d.).

After the crisis, the City of Cape Town developed a Water Strategy to strive towards a more resilient water future for the region. The five strategies include: safe access to water and sanitation; wise use; sufficient, reliable water from diverse sources; shared benefits from regional water resources; and a water sensitive city. It is believed that supporting these strategies will secure water and improve the quality of life for Capetonians ("City of Cape Town," n.d.).

Impact to Fire Protection and Fire Protection Systems

During restrictions, water pressure was decreased in the system, which could lead to inadequate protection of premises. Due to the invasion of alien plant species, the region has been at higher risk of wildland fires. In an already dry area, if fire protection systems are ineffective, a structure or wildland fire could easily be very destructive.

2021 Texas, USA Arctic Blast Water Crisis

In February 2021, the central United States was hit by a massive winter storm over the course of two weeks, causing large scale infrastructure failures across the region and in particular, Texas. This winter storm, besides causing large scale power failures, also damaged the water supply systems throughout the locations hit by the storm. These storms left more than 12 million people without access to water due to pipes freezing and bursting (Talmazan, 2021). These water supply shortages also caused many, if not all, of the water-based fire protection systems to be rendered inoperable, due to their reliance on a steady flow of water. The winter storm was one of the worst in recent history. The city of Austin and Travis County After Action report highlights over 130 recommendations to improve infrastructure and be better prepared for future weather events. The report also highlighted significant gaps in planning, response coordination, and staffing (County, 2022). It took months to repair the damage to the infrastructure that was damaged by the storm. This crisis highlighted how unprepared the state of Texas was for a natural disaster event, but understanding the geography, population, water supply configuration and usage, and mitigation efforts will help to understand how this area could be impacted by a water supply shortage.

Geography and Population

The state of Texas is located at the southern border of the United States with Mexico. Texas has quite a storied history as it was first an area held by Spain, then France, then Mexico, then it stood as an independent nation until it joined the U.S. in 1845. As it is the second largest state in the nation it is home to a variety of climate zones. Typically, the climate in Texas is warm arid in the west and warm humid in the east near the Gulf of Mexico. Texas has an average rainfall of 27" but this varies wildly across the state, from 14" in the west to over 54" in eastern areas (WeatherSTEM, 2017).

Texas has a population of more than 29 million per the 2020 Census (Bureau, 2020). As the winter storm did not hit every corner of Texas, its impact was felt by more than half of the current population, many of which were in the largest cities, including Houston, San Antonio, and Dallas and various outlying suburbs. The largest cities experienced weeks long water shortages along with not having access to other essential services, such as electricity and food supplies.

Water Supply Configuration and Usage

The state of Texas water supply is regulated by the Texas Water Development board. Texas water supply is split about 50 percent groundwater and 50 percent surface water, with some various percentage points from the reuse of treated wastewater. The water supply found on the surface is from 188 major reservoirs and 15 river basins (Spencer Grubbs, 2019). This water is then piped to various agricultural land or cities and redistributed through pumping stations. Based on a 2016 report, it was found that Texas used nearly all of its available water supply, with the majority of that supply going towards agricultural use or municipal use.

Leading Causes of Water Depletion

The main cause of water shortages was caused by the winter storm freezing the vast majority of pipes and shutting down most of the infrastructure in place in the state. Texas is on a separate power grid from the rest of the U.S. and the power grid was also partially shut down during the storm. This grid is run by the Electric Reliability Council of Texas and was very close to complete failure across the state before partial shutdowns were implemented. The shutdown of the power grid also affected water pumping stations that would have supplied water, had the pipes not been frozen.

This led to a complete lack of water availability to much of the population, including emergency response. If a fire were to happen, the only water available in this situation would have been from fire fighter's tanker trucks, which can only supply a limited amount of water. The majority of the population was also relying on bottled water to survive. This led to a mass depletion of bottled water in stores during the storm, especially with the storm shutting down most shipping routes leading to a vast majority of Texans being left without water.

Mitigation Efforts

At present, Texas is not currently adopting any new provisions to protect its water supply. There are a few changes being made to help protect the electric grid from failing the next time it is overloaded, but this will not directly protect the water supply, outside of ensuring the pumps will not fail. Texas authorities are currently aware of the issues regarding lack of adequate water supplies and are pushing for policy changes.

Impact to Fire Protection and Fire Protection Systems

During the crisis, water supplies were very limited to all Texans. The electric grid, being separated from the rest of the country's power grid, was not able to keep up with the increased demand. Since the electric grid was not able to be supplemented by the rest of the country, water pumping stations in Texas were unavailable. This lack of water affected the entirety of the fire protection systems that were dependent on that water supply. Without these systems in operation, the risk of not being able to control and suppress a fire was greatly increased for most occupancies.

Spain Freshwater Crisis

Spain is currently in the midst of a freshwater crisis. The region has been hampered by a reduction in the typical amount of rainfall, which has reduced the available amount of water in the country. Since the majority of Spain is used for agricultural purposes, this lack of water has far reaching repercussions. This lack of rainfall is also happening in combination with a drought leading to a water crisis. Farmers are resorting to illegal methods of obtaining water, such as drilling into the groundwater sources. This depletes the groundwater sources far beyond a sustainable rate and will deplete them far beyond their capacity to be refilled naturally (Post, 2020).

Geography and Population

Spain is located on the southwestern side of Europe, inhabiting the Iberian Peninsula, with coastline along the Mediterranean Sea. The country has a diverse geography including mountains in the northwest, a large central plateau, and plains leading to the coast on the east. The southern portion is desert, likely related to the Sahara to the south. The climate is typically divided into two zones. Areas close to the ocean are more coastally climate, as stated earlier there is also a desert region to the south of the peninsula. The region is typically humid with high rainfall due to the presence of the sea and the mountains. The average temperature is typically around 43 Fahrenheit near the coast with an average rainfall of around 38 inches (Gines Richardson, 2022). The population of Spain is 47.35 million as noted by a 2020 census.

Water Supply Configuration and Usage

Spain is served by multiple freshwater basins. Central Spain is served by the largest, the Upper Guadiana basin; Eastern Spain is served by the Segura River basin; and southeast Spain is served by various smaller basins. Freshwater basins are typically refilled from the natural water cycle, mainly contributed to by rainfall. The rainfall in Spain varies from 650 millimeters to up to 1,000 millimeters in the coastal areas (Gines Richardson, 2022). The country also has various glaciers in the mountains that feed streams and rivers leading throughout the area. The glaciers have been melting at a much faster pace in recent years leading to a much more strained supply in the summer months. There have been a few desalination efforts in Spain, but the majority of the water reclaimed is only used for urban purposes and very little has been devoted to agricultural needs. According to a report, currently only 16% of the desalination capacity is being used.

According to a 2015 report, agricultural water usage accounted for 67% of all available water being used in Spain. The other main uses are for domestic, i.e. for residential and business uses, and for energy, typically cooling of nuclear power plants (OECD, 2015).

Leading Causes of Water Depletion

Outside of the massive factor of climate change melting the glaciers located in the Pyrenees mountains, farmers in agricultural regions have been drilling boreholes into the groundwater resources to steal water from the already taxed water infrastructure. These actions are illegal per the Spanish government. Farmers water supply is being rationed to help to try and contain the water supply shortage, but these farmers are using these boreholes to help with irrigation for farms and ranches. This depletion of the groundwater is leading to villages not having any water supply. Villagers are having to use bottled water for any activity using water (Cuellar, 2021).

The lack of water availability is believed to be a combination of supplies drying up and the remaining supplies being non-potable. The non-potability of the remaining supplies is primarily due to the presence of nitrate, which is typically used as a fertilizer for agricultural uses. Many of the existing aquifers rely on rainfall to replenish them, but the climate change affecting the region is limiting the rainfall that is typically abundant. Rainfall in Spain is projected to decrease anywhere from 5% to up to 30% in the next 20 years (Post, 2020). As it currently stands, there is not enough available water in the region to both irrigate all the farmland and supply all of the population. The overuse of the water supply combined with the runoff of fertilizer from agricultural activities is leading to Spain's water being inadequate for all parties involved. There were also a couple of instances where dams were drained to produce electricity through hydroelectric means cheaply during a drought. This further exacerbated the limited water supply to villagers. (Post, 2020)

Mitigation Efforts

As it currently stands, there is limited action being taken in Spain to try and fix the water crisis. There are a couple of politicians campaigning on the premise of stopping the illegal tapping of the existing groundwater and pushing for sustainable water initiatives (Oyj, 2020). This is a much greater effort than they are making it seem, as there are hundreds of thousands of farmers located in Spain and it would be impossible to determine everyone that is tapping into groundwater. Currently, satellite imagery and drone surveillance is being used to try and track some of the offenders, but there is not a recognized plan of action to try and deter these farmers.

Impact To Fire Protection Systems

As it currently stands, there are not many active fire protection systems in place in Spain. Specifically, not very many fire sprinkler systems using water are available. However, the lack of available water could inhibit firefighters trying to combat active fire scenarios. Without water, firefighters will not be able to efficiently fight fires, and this could lead to fires getting out of control and possible spreading. Combined with the drought and the current conditions, this could lead to WUI fires starting and firefighters being unable to contain these fires. Large enough WUI fires can ravage the large swaths of farmland in Spain, and if left unchecked, these fires can spread to the urban centers and cities.

Australia Water Crisis

Australia is experiencing its own water supply crisis. The country/continent has been experiencing a period of extreme drought that has lasted several years. The rainfall has also been decreasing steadily across the last few years. These factors in combination are leading to a major water supply shortage across the country. Much of the population is located along the coast in large cities, but the Outback, located in the center of the country is much less populated and is used for more agricultural purposes.

Geography and Climate

Australia is a large continent located in the southern hemisphere. The country consists of mostly arid low desert areas. But since it is such an isolated region, there are a wide range of climates found here. In the south and east areas are temperate fertile plains, and the north area is very similar to a tropical climate. There are approximately 23.5

million people living in Australia according to a 2018 census, with approximately 85% of the population living in cities or urban areas. As much of the area is desert, the annual rainfall tends to be on the lighter side, averaging only about 22-25 inches throughout much of the outback region, with coastal cities receiving upwards of 45 inches of rain per year (Government, 2021). Much of the land in Australia, is considered agricultural, even though much of it is not actually farmland. The region known as the Outback covers approximately 70% of the continent. Australia itself is facing many issues concerning water. Droughts are very common in the country and seem to be a regular occurrence (Sousa Júnior et al., 2016). Another issue that may be relevant is the significant desertification in the country, meaning that fertile land is becoming desert, which creates its own water supply issues.

Water Supply Configuration and Usage

Water supply in Australia is primarily driven by rivers, large freshwater reservoirs, and groundwater basins, as there is not enough water in each source to reliably depend on a single one. In recent years because of the increasing water shortage and the droughts in Australia becoming much more significant, desalination plants have been built in many of the coastal cities. These desalination plants have been constructed to supply most of the water supplies necessary in these cities, but most are not currently operating at full capacity for one reason or another. Most of the actual water supply piping networks are only available in the large urban cities.

Much of the Outback is supplied differently, usually from rivers or tanks, since there is a vastly smaller number of people living in these regions than the cities. Approximately 68% of the country’s freshwater has been devoted to agricultural use, with around 21% used in the urban water systems (Elmahdi, 2015). Since much of the population living in cities can be supplied by desalination plants, the main emphasis on water conservation is focused in the agricultural areas.

Leading Causes of Water Depletion

There are a couple of leading causes of water depletion in Australia. Droughts are common in the region, but they have been getting worse in the last few years according to a report from the Australian Government (Drought in Australia, 2012).. These longer lasting droughts are considered to be a consequence of climate change. According to the same report these more powerful droughts will also ultimately affect the agricultural production of the country, which is one of its most significant industries. Along with these droughts, other factors impacting the country's water supply are WUI fires accompanying these droughts, making them much more impactful where fires sweep through an already water starved region. There is also the considerable amount of desertification happening in the region, resulting in the Outback region growing larger every year. There are a couple of lesser factors affecting the water supply such as poor farming practices, resulting in the soil in the regions requiring much more water than normal.

Mitigation Efforts

Australia seems to be taking a very active stance in order to repair and replenish its water supply. The country is actively taking steps to ensure that the abundance of droughts happening will not completely derail the country's agricultural industry. The country is currently implementing desalination plants to supply much of the coastal urban centers. These plants are not currently operating at full capacity. The Australian government is also running an education and information campaign to teach farmers and other agricultural industries how to help manage and prepare for the droughts. They are also offering incentives to farmers who use sustainable farming practices to help mitigate the effects of the prolonged droughts.

Impact To Fire Protection Systems

Many of the areas affected by the water supply issues do not have active fire protection features, such as fire sprinkler systems. The areas in the Outback are typically served only by fire and emergency personnel, which would be affected by the drought as they need water to fight the WUI fires that occasionally accompany these droughts. In the urban coastal cities, many buildings are served by active fire protection systems that require water. These cities do not have the same water supply issues as the agricultural regions, so they are less affected by the droughts. The cities can also use the water supply from the desalination plants to serve their active fire protection systems.

Effects on Water Supply

Survey of Stakeholders

The gap in the literature is clear when it comes to the impact of water supply stress related to water-based fire protection systems as well as manual fire department suppression efforts. Fire protection engineers and designers are not typically included in the conversation when discussing water supply stress in areas. Concerns are typically focused on domestic and agricultural use. As such, the conversation of fire protection systems and water supply stress is in the beginning stages with the fire protection engineering community. A brief survey was developed to begin to understand perspectives of water supply stress and the impacts to fire protection systems.

Survey Participants

The survey participants were varied across the world and across various occupations that have experience with water supplies. Responders were asked to provide their location and occupation. The vast majority of respondents were from the United States of America, with others being worldwide. Asia, Europe, Africa, and South America were represented as well. As water supplies shortages are a global issue, opinions and responses from across the globe are welcome and appreciated. Response from all sorts of workers who could be involved with water supplies were also represented. A majority of the responses were from Fire Protection engineers, but Authority Having Jurisdictions, fire protections systems designers, installers, and technicians, and insurance workers were also fairly well represented. The survey was sent out through various sources, including SFPE and other outlets.

Survey

The survey was developed to try and gauge various regions' attitudes and respective plans regarding their water supplies. As stated before, the responders were first asked where they were from or the location of their work and their occupations. Then a question was asked to determine where/how they received the majority of the water, be it from rural or city water supplies and where that water came from, such as lakes, groundwater, or desalination plants. Once the where and the how of the water supply was asked, responders were then asked if the communities they worked with had a plan in place for water shortages. If their community was stated to have a plan in place, responders were asked if the fire department was involved and what proposed solutions the plans offered. Next, a question of whether or not they had worked on a project that was subject to a water supply shortage and how that effected the project was asked.

Questions were also asked about the possible causes of a project’s water shortages. The survey then also posed questions regarding who should be involved in a community planning effort to prevent a water supply shortage and how such a shortage could impact fire departments. There were also free response portions for all questions allowing respondents to answer accordingly.

CHAPTER IV

FINDINGS

There is very little information on urban water shortages. The lack of information on how to mitigate water shortages in urban areas indicates that urban areas may not be prepared to deal with water shortage crises, much less the impact that such a crisis would have upon the fire protection systems present. There is a minimal amount of information about how rural agricultural areas have dealt with water supply shortages, but it is not enough to confidently say most agricultural areas are well equipped to deal with water supply shortages. The lack of literature applicable to water supply shortages is worrying, when there are more and more water supply shortage crises happening every year.

Water supply systems are generally discussed when research about climate change is done. There is a lot of focus on ensuring that people will have access to clean and reliable water supplies for domestic use. As water supply systems pertain to fire protection systems, there is not much research done on the implications of a water shortage on fire protection systems, whether those protection systems are items such as sprinklers or a more active role in suppression due to fire fighting. The lack of a reliable water supply system will drastically decrease the effectiveness of fire protection systems in buildings and will also hinder the active suppression efforts of firefighters when they do not have the required water to combat a fire emergency.

There are various requirements/policies in place regarding fire protection systems in differing regions. The vast number of different requirements should also be examined when trying to determine how a water supply shortage will affect various fire protection systems and/or fire department suppression and response efforts. In the U.S, many buildings are sprinklered and therefore require an adequate and reliable water supply. These sprinklered buildings are used in conjunction with fire department response and suppression efforts to ensure that a fire emergency is combated effectively. Other regions rely more heavily on fire department response and suppression efforts, which also rely upon an adequate and accessible water supply. Understanding how differing regions heavily depend on water supplies for their various fire protection systems, whether it be through sprinkler systems or through fire department response and suppression, is key to understanding how to develop policies and plans to help to combat water supply shortage issues.

Data Analysis

Question 1 was to provide your Country of Residence or Global Region. There were 230 responses to this question, with the large majority of respondents located in the United States. Removing the 181 respondents located in the U.S, the following graph indicates the remainder of the responses being from throughout the world.

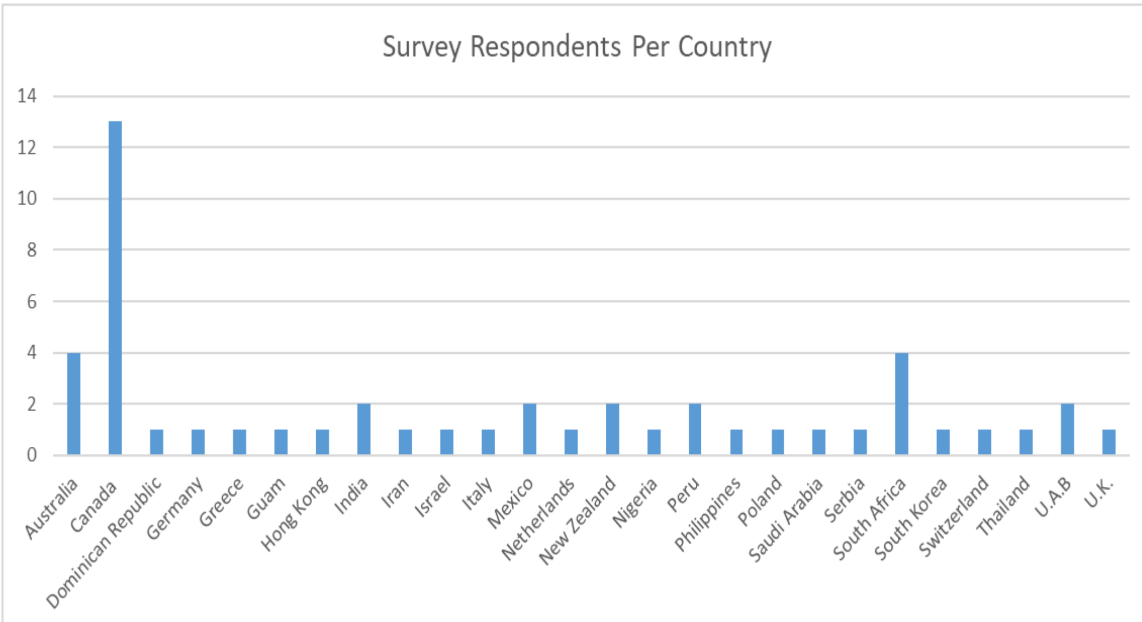

Figure 2a. Question 1: Where are you from?

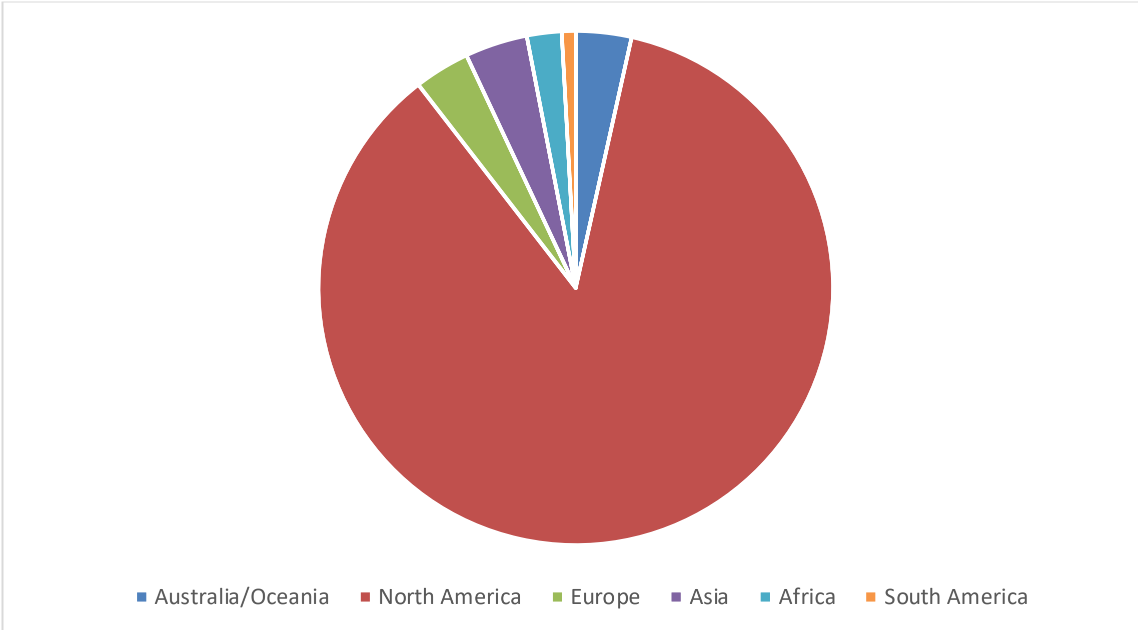

Figure 2b. Question 1: Where are you from?

Question 2 asked respondents to provide their position or industry. There were 237 responses to this question. Over 50% of all respondents were fire engineers. Respondents that indicated other, typically fell into fire service categories or fire protection engineers serving in a different capacity (owners' representative, etc.).

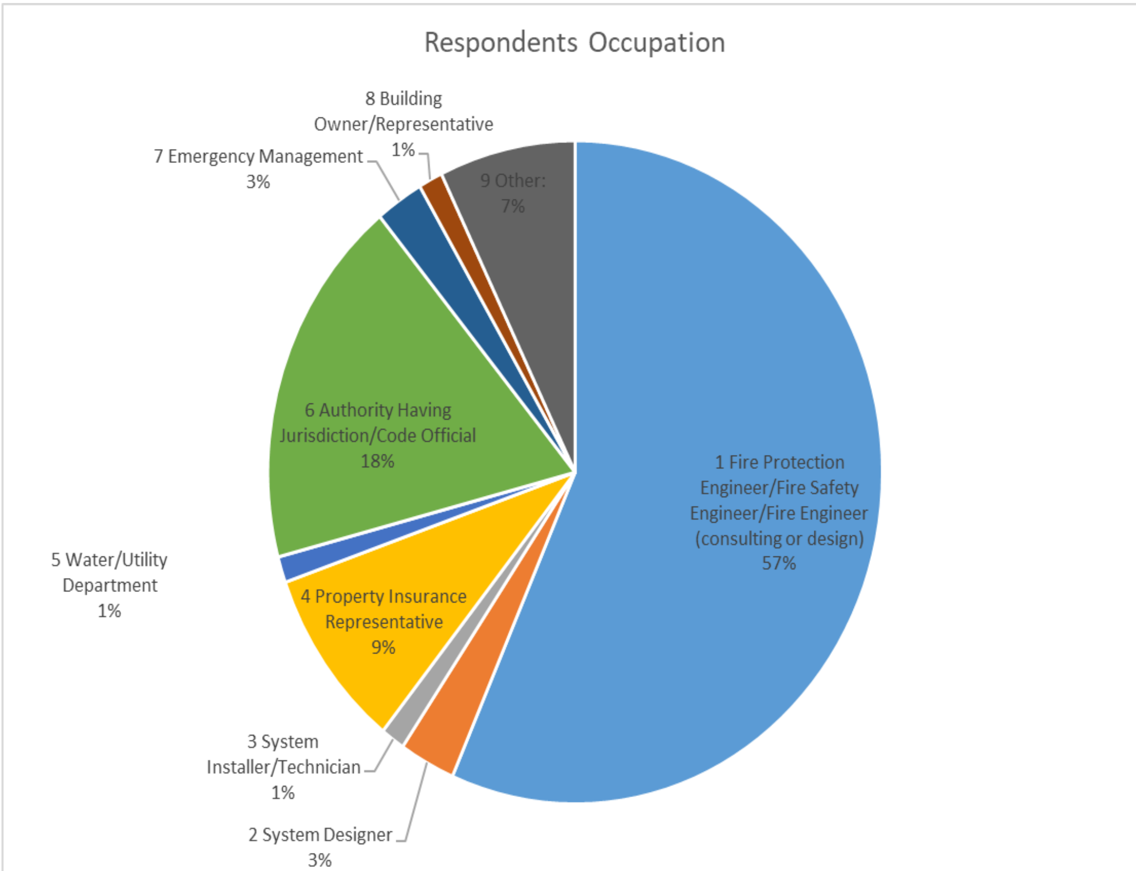

Figure 3. Question 2: What is your position in industry?

Question 3 asked respondents to provide the type of water supply they dealt with primarily on projects. This question included a "select all that apply" option. Of the 468 responses, they were split primarily between city water supply with 46%, private water supplies with 29%. and rural water supplies with 24%. The other responses indicated the use of wells, tanks, and reservoirs.

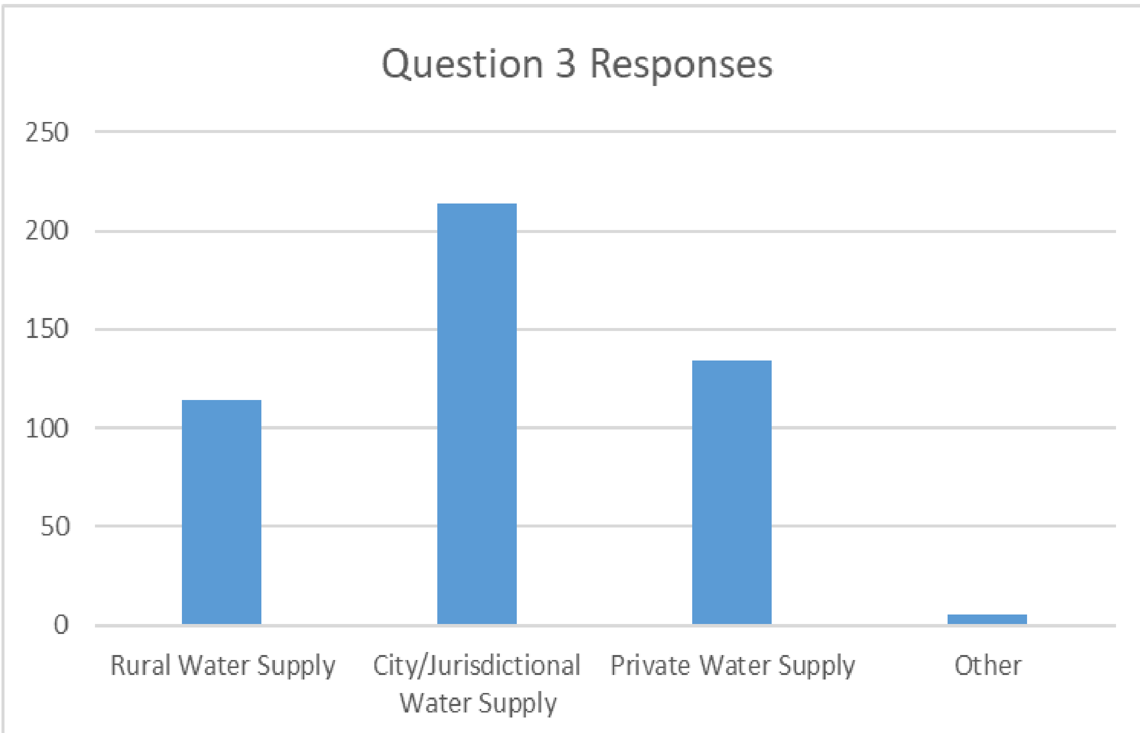

Figure 4. Question 3: What is the primary water supply dealt with?

Question 4 posed the question of where the water supply indicated in question 3 primarily came from. There was also a “select all that apply” option. The overwhelming majority of the 354 responses stated that their water supply systems were primarily fed by lakes, rivers, and streams with over 50% of responses, followed closely by groundwater sources with 38%.

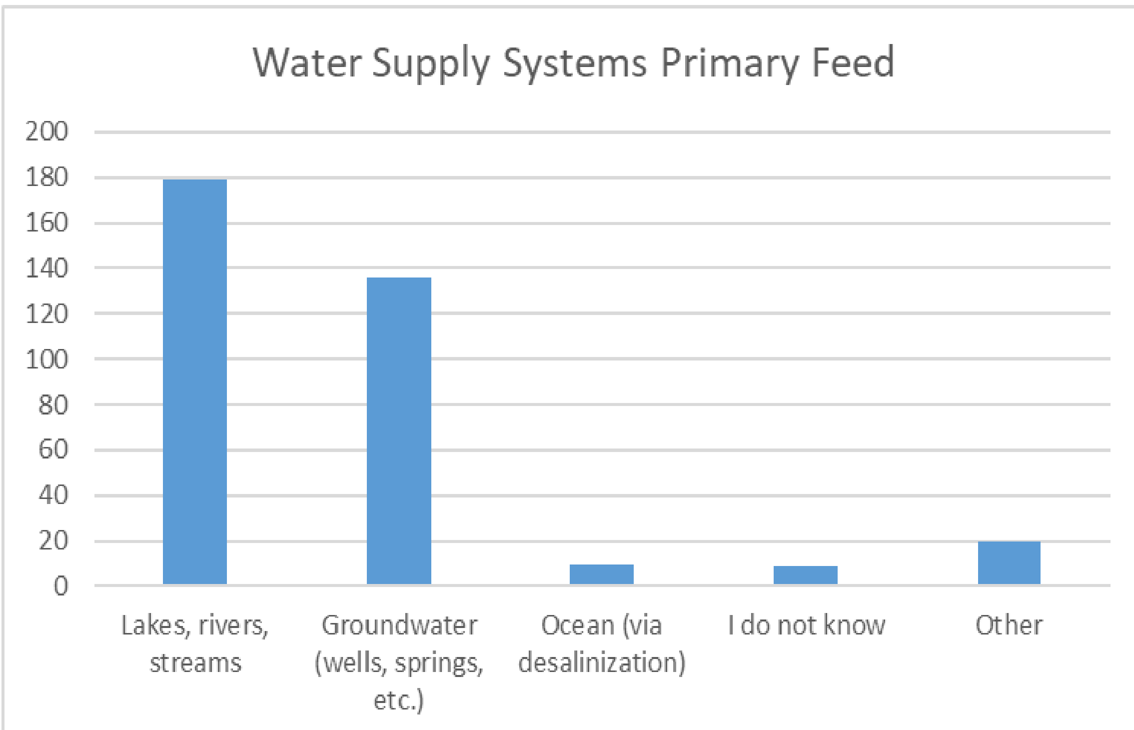

Figure 5. Question 4: What is the primary feed of the water system?

Question 5 asks if communities had a plan in place for a water supply shortage. The 237 responses were split between 39% saying yes and 38% saying they did not know or were not aware of a plan in place. 17% of respondents said they did not have a plan in place. Other responses indicated that respondents worked in multiple areas, and it varied by location.

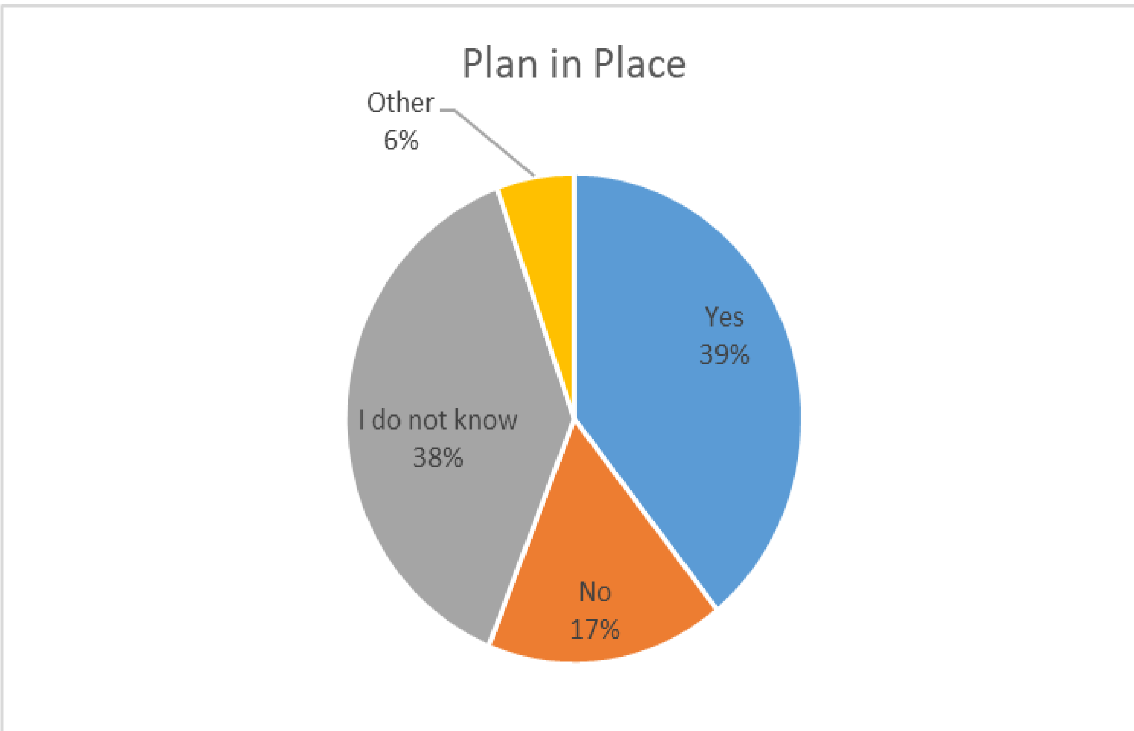

Figure 6. Question 5: Is there a plan in place for a water supply shortage?

A continuation of the previous question, Question 6 asked if fire protection systems or fire department response efforts were discussed in the plan for water supply shortage. Of the 220 responses, the majority, 57% answered they were not aware if suppression efforts were considered. Over a quarter of respondents, 26%, answered that these efforts were considered when making a plan for water shortages.

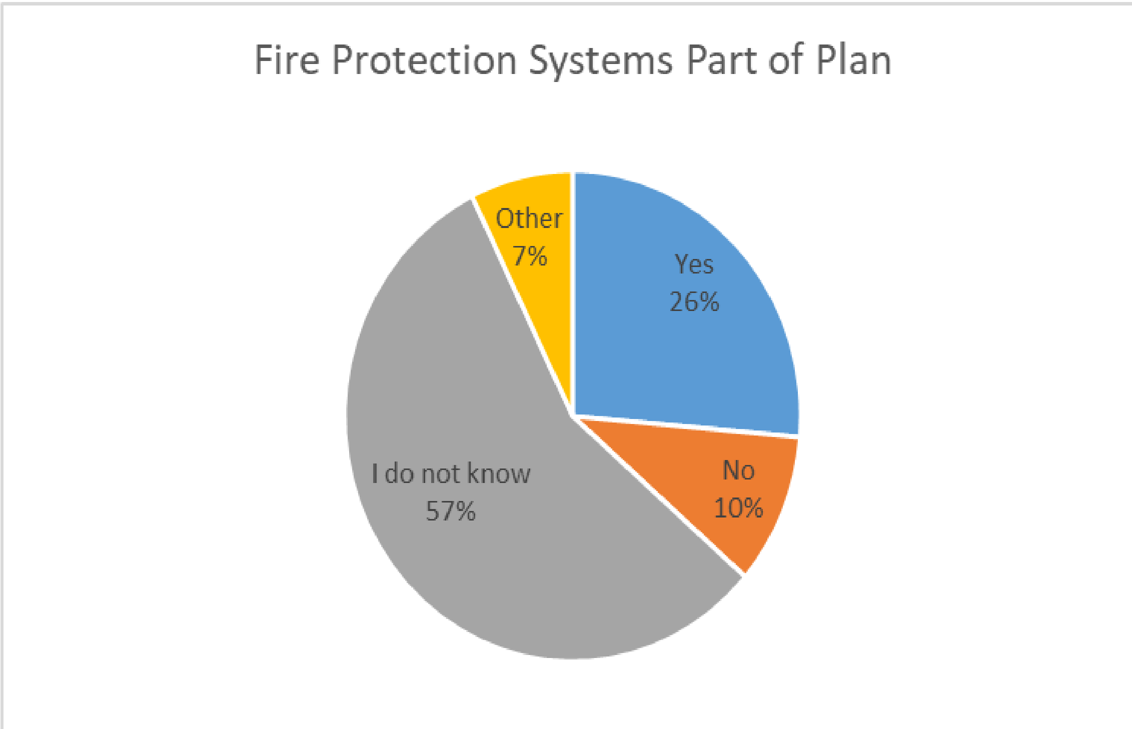

Figure 7. Question 6: If a plan is in place, are fire protection efforts a part of that plan?

Question 7 continued the previous line of questioning, asking if a plan was in place, what were the proposed solutions, with a “select all that apply” option. Of the 298 responses, the majority of respondents indicated they did not know. Of proposed solutions the majority indicated that supplemental water supply, reduction of water pressure in system, and rationing of public water supplies where the best options.

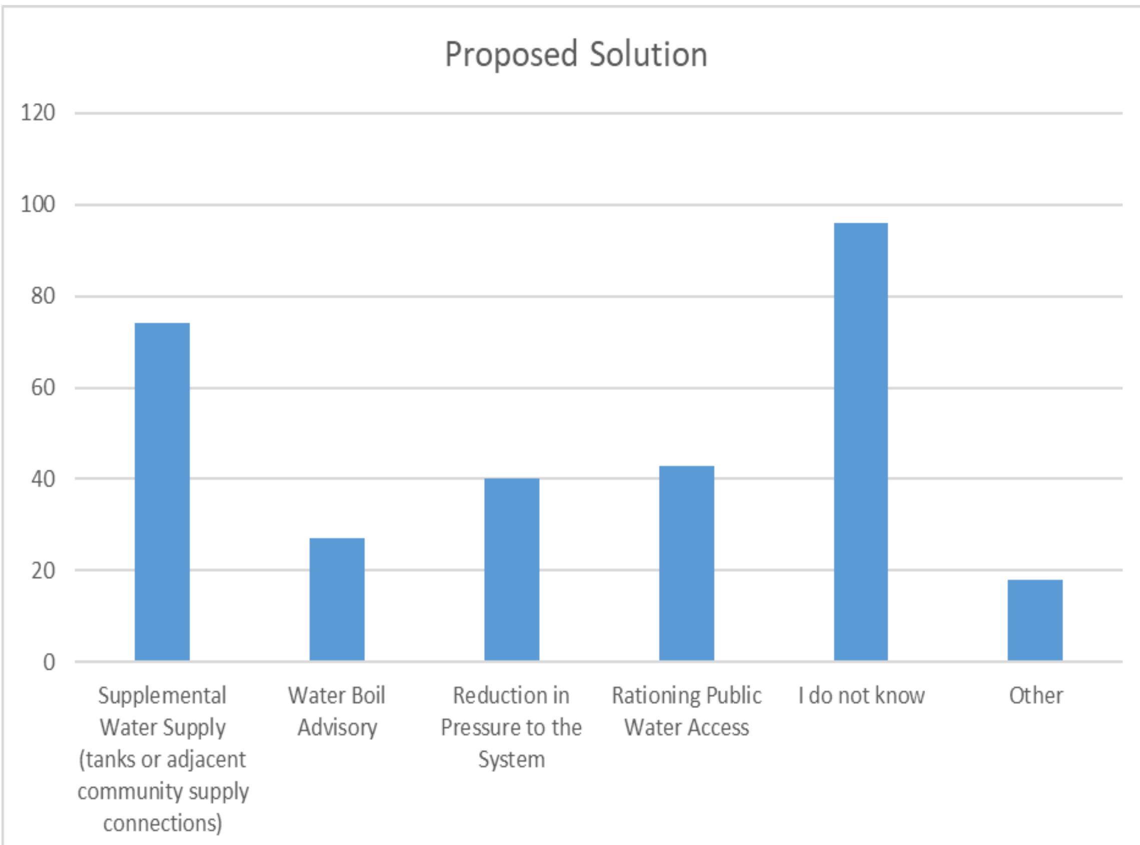

Figure 8. Question 7: Proposed solutions in a water supply shortage plan?

Question 8 posed the question asking if respondents worked on a project or in a jurisdiction that were subject to water supply shortages. Over 75% of the 237 responses were yes, they had worked in such an area. Of the other responses, one such answer was that in hindsight, they had worked in a region that had insufficient capacity for droughts.

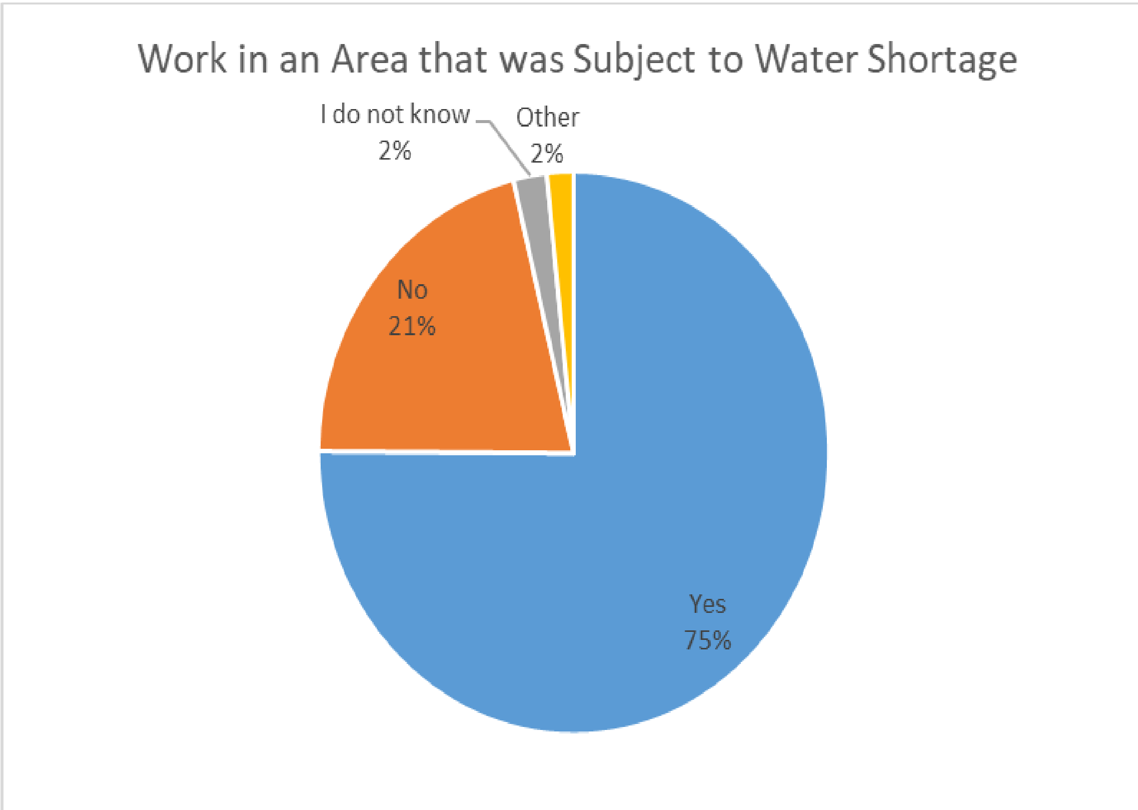

Figure 9. Question 8: Does the respondent work in an area subject to a water shortage?

Question 9, a continuation of the prior question, asked what sort of water supplies were present in the project/jurisdiction that were subject to water supply shortages. Of the 203 responses, 60% were city/jurisdictional water supplies, with rural and private water supplies sitting at 17% and 16% respectively.

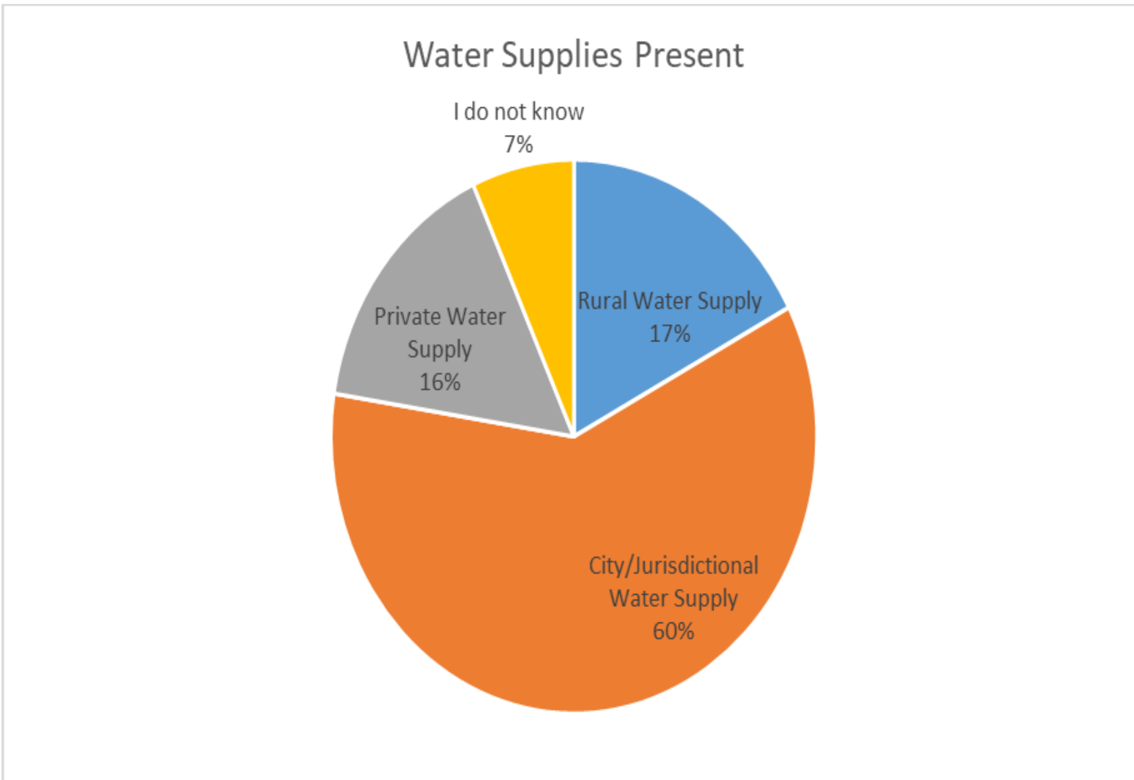

Figure 10. Question 9: What kind of water supplies are present?

Question 10, continues the line of questioning from the previous question, asking what sort of water supply was feeding the water supply systems. There was also a “select all that applies” option. Of the 245 responses, 42.86% were lakes, rivers, and streams. Groundwater was the second most prevalent with 38.37%. The other responses also indicated that rainfall was an additional source of water supply.

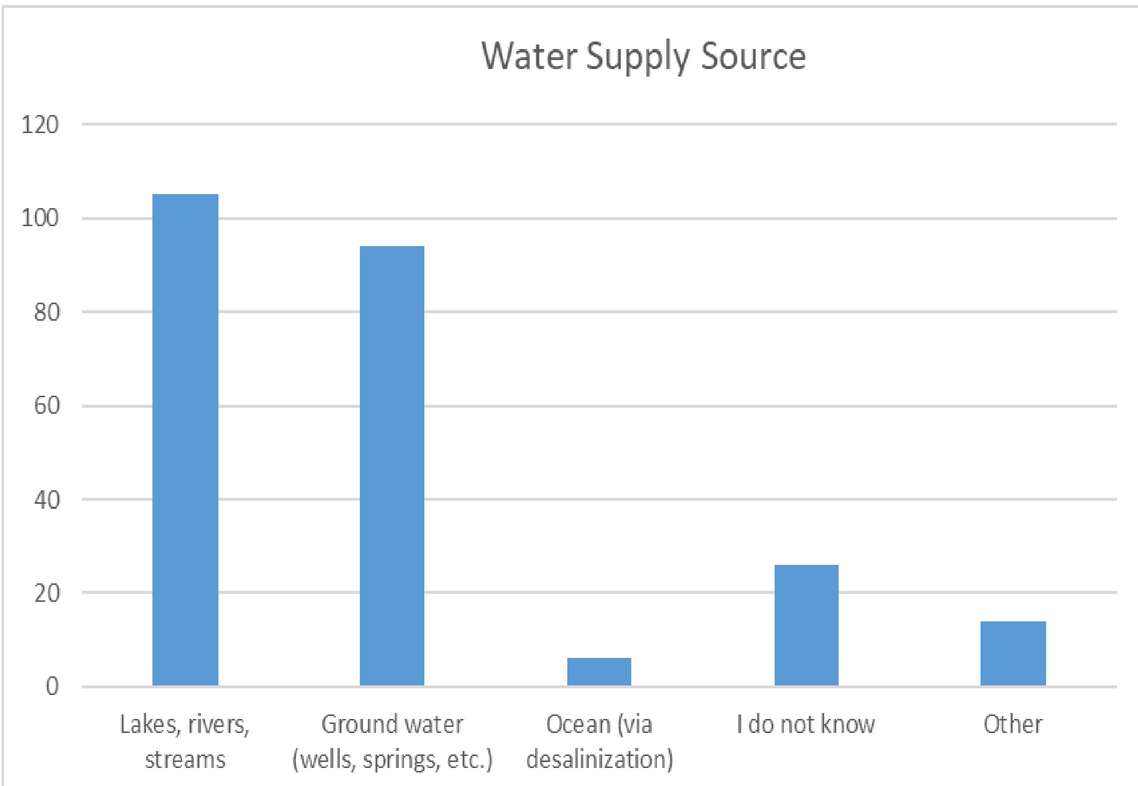

Figure 11. Question 10: What is the source of the water supply?

Question 11 asked what the specific cause of the water supply shortage was. There was also a "select all that apply" option. Of the 332 responses, the largest issue was found to be inadequate infrastructure at 40.06%. Other leading causes were lack of rainfall, population growth, and mechanical failure of water supply. There was a significant amount of free responses to this question, but the majority of them can be attributed to inadequate infrastructure.

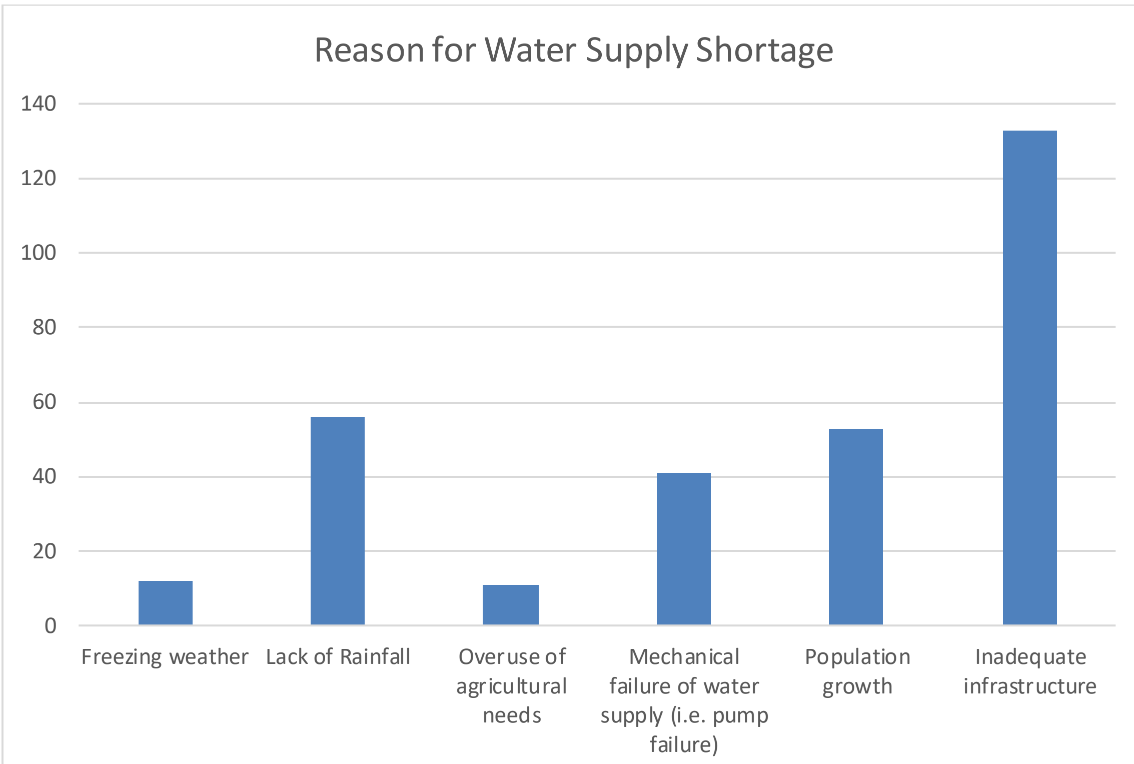

Figure 12. Question 11: What was the cause of the water supply shortage?

Question 12 posed the question of what fire protection systems were impacted by a water supply shortage. There was also a “select all that apply” option. Of the 294 responses, 34.69% indicated a sprinkler system inadequacy, followed by respondents not being aware of an event at 30.61%. The majority of free response questions can be attributed to sprinkler system inadequacy, although one response also noted that they were lucky a fire event had not occurred simultaneously with a water supply shortage.

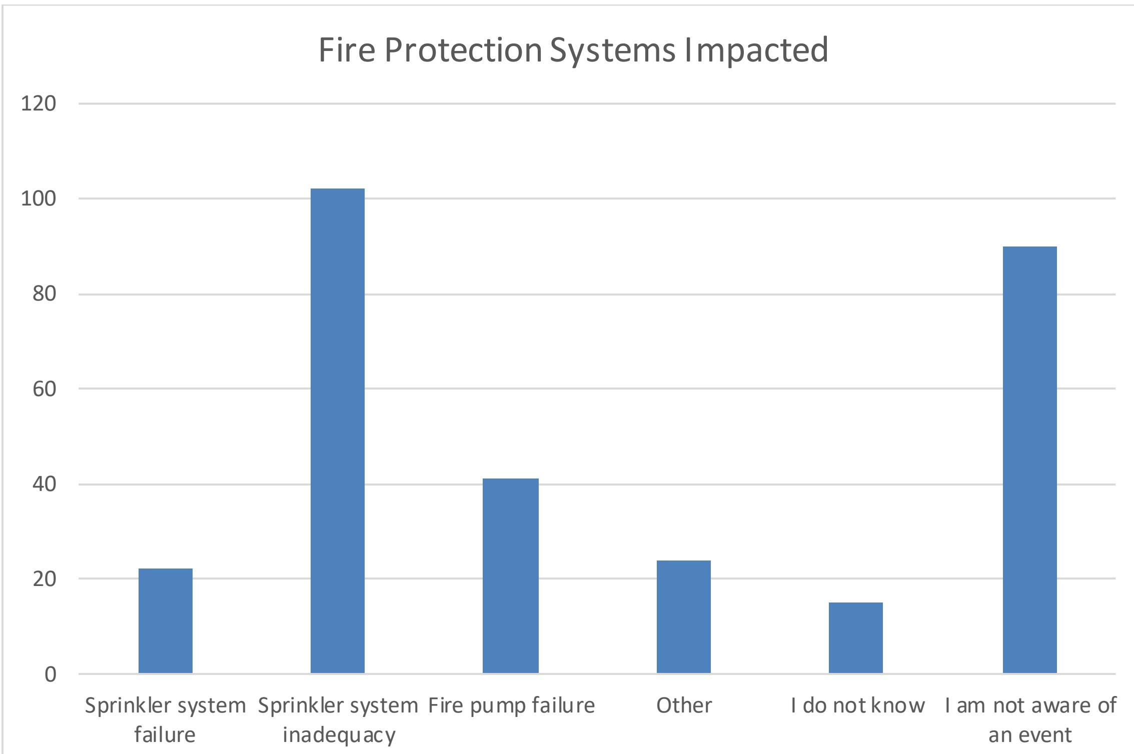

Figure 13. Question 12: Which fire protection systems were impacted by the water shortage?

Question 13 asked the question of if a water shortage event impacted fire department response and suppression efforts. There was also a select all that apply option. With a total of 284 responses, the main answers were not aware of an event at 36.62%, suppression efforts unsustainable due to water shortage at 22.54%, and unable to provide suppression effort at 14.44%.

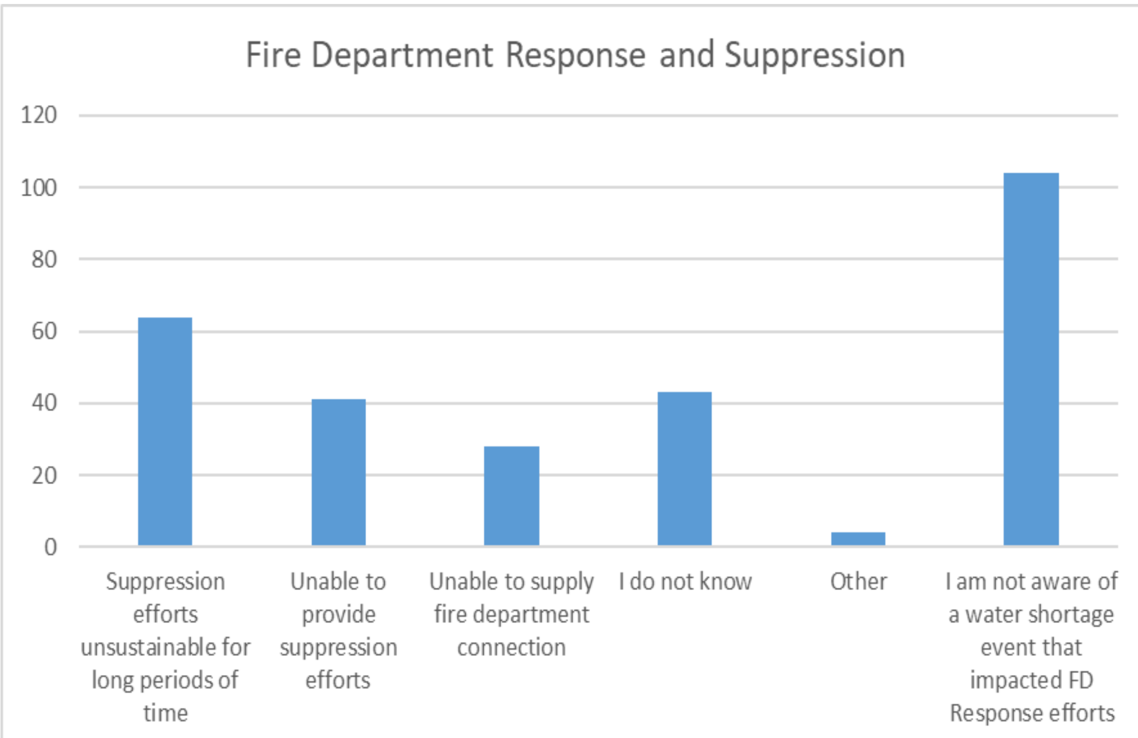

Figure 14. Question 13: Did the water shortage impact fire department response and suppression?

Question 14 asked, in areas that have not experienced water shortages, how could a water supply shortage impact fire protection systems? There was also a “select all that apply” option. With 473 responses, the majority of answers were sprinkler system inadequacies at 40.17%, fire pump failures at 27.27%, and sprinkler system failures at 24.52%.

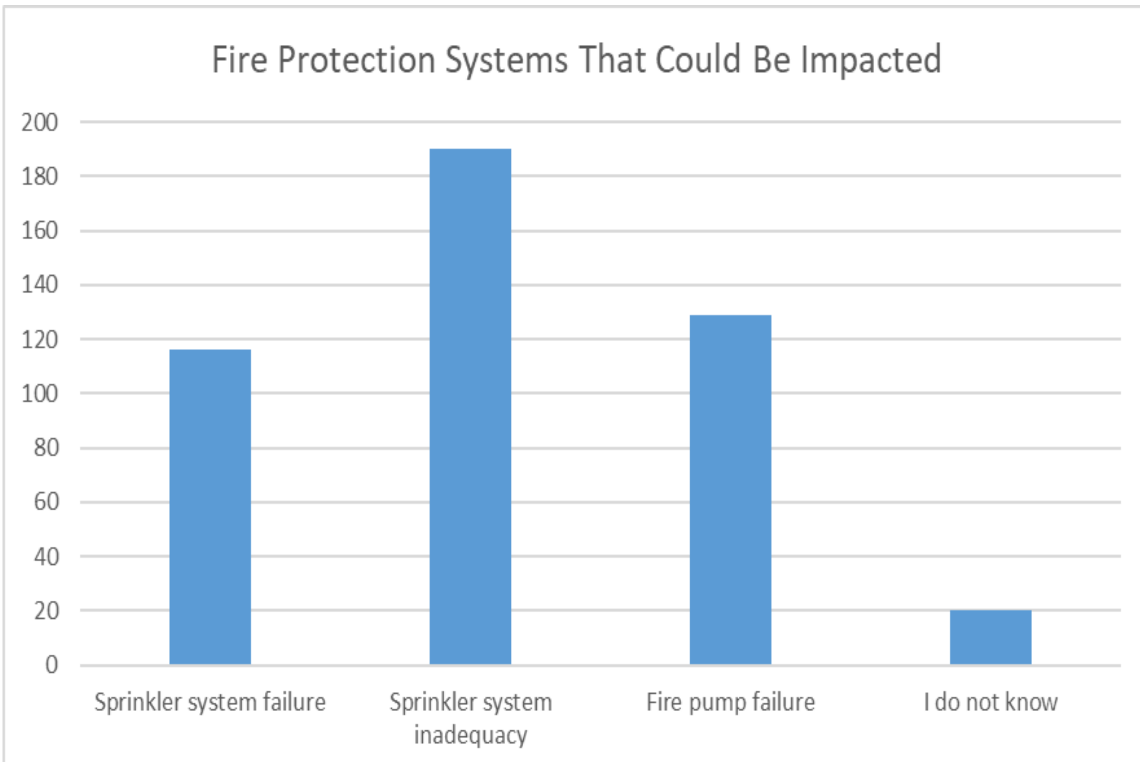

Figure 15. Question 14: Which fire protection systems can be impacted?

Question 15 asked in areas that have not experienced water shortage, how could a water supply shortage impact fire department response and suppression? There was also a "select all that apply" option. With 452 responses, the answers were about evenly split between suppression efforts unsustainable at 38.05%, unable to provide suppression efforts at 30.75%, and unable to supply fire department connections at 27.65%.

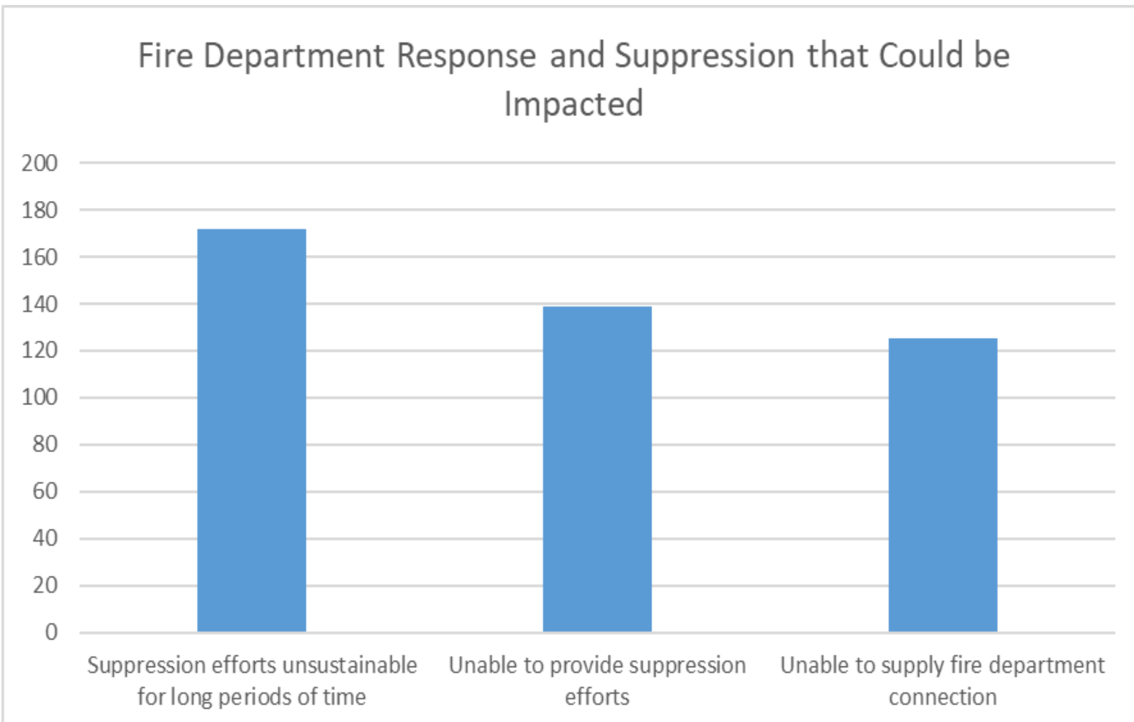

Figure 16. Question 15: How could a fire department response and suppression be impacted by water shortage?

Question 16 asked for responders to include all stakeholders that should be involved in planning for a water shortage. This question also included a "select all that apply" option. There were 1505 responses to this question, giving this question the most feedback received. The largest stakeholders were indicated as being water supply/utilities representatives at 14.35%, fire department/fire marshal at 14.09%, and fire protection engineers at 12.43%, with various other stakeholders that should be involved as indicated below. Of the other responses, codes and standards companies, the health department, and department of natural resources were also mentioned as possible stakeholders that should be involved.

Figure 17. Question 16: Which stakeholders should be involved?

Question 17 was a free response question asking for additional comments and feedback on water supply systems dealt with and other issues with water supplies. The majority of free response answers can be attributed to there being inadequate infrastructure for water supply systems. Contamination of water supplies was also a large contributing factor for water supply issues. Some respondents also pointed out that politics in their local region will also affect the water supplies by way of not providing proper funding for adequate infrastructure. For more information on these free responses, see Appendix A.

Discussion

Based upon the literature review and gap analysis, the effect of water shortages on fire protection systems is apparent, but not well known. There are a variety of possible ways to combat this lack of knowledge. Implementing policy changes at all levels of government to ensure that water supply infrastructure is adequate will be key to maintaining a reliable water supply. Education of key stakeholders about how a water shortage can happen, and the key effects of that shortage will help to keep stakeholders aware of such situations. There is also much research to be done in this field that will be discussed.

CHAPTER V

CONCLUSIONS

In accordance with the results of the survey, a few things are made clear. In areas that were subject to water shortages, plans to account for the water shortage typically did not include water-based fire protection systems. The lack of these systems inclusion in the plans is a deficiency that will cause issues if a fire event happens in tandem with a water shortage.

There was also large number of responses that indicated respondents were either not aware of a water shortage plan or were not aware of the inclusion of water-based fire protection systems within said plan. As noted, water-based fire protection systems will be affected negatively by a lack of water or a water shortage. Another typical theme was the inadequacies of water supply infrastructure. Areas that do not have available or reliable water supply infrastructure in place will also have detriments on the availability of water for fire protection systems.

One of the recommendations is the development of policies that will upgrade infrastructure to provide adequate and reliable water supplies and also to maintain those systems to keep them reliable. Current practices in some areas have alternative solutions for how to handle water shortages, but when fire protection systems are involved, there are very few solutions out there. Creating and developing policies that provide for means to upgrade current water supply infrastructure to help to combat water shortages will also help to improve fire protection systems performance when water shortages occur. Based on the case studies, different countries seem to understand that water shortages are a major problem, and they are slowly coming around to determining how best to ensure their citizens have access to water. However, countries still are not recognizing the implications of losing their access to fire protection systems when experiencing a water shortage. This will need to change, so that countries are adequately prepared when fire events occur simultaneously with a water shortage events. As indicated by the results of the survey, one of the major problems with maintaining an adequate and reliable water supply is inadequate infrastructure. Upgrading and maintaining existing infrastructure when it becomes outdated or obsolete is one of the key provisions when accounting for water supply shortages.

In tandem with the development of policies to upgrade water supply infrastructure, the development of a plan to account for water shortage should also be developed in areas that have not already developed plans. These water shortage plans should include various stakeholders, as indicated above, and should be adapted to fit each area’s specific landscape and water supply configuration. The development of such plans should be tailor-made to fit each community’s needs. Including all of the various stakeholders that may have an interest or possible solutions to problems will help to ensure that the water shortage plan will be as thorough and robust as it can be. Figure 18 below shows the stakeholders that should be involved when planning for and responding to water supply stress or scarcity.

In countries with easy access to oceans or seas, desalination plants would provide a reliable water supply. Many countries have access to a large body of water such as an ocean or a large saltwater sea. While these bodies of water may not be fit for human consumption without proper desalinization, many countries already have desalinization plants in place. Ramping up production and the amount of these plants will lead to a reliable and easily accessible water supply in these areas. Creating such a reliable and accessible water supply will also ensure that fire protection systems will have the necessary water and pressure to protect the facility or hazard in which it is installed..

Inspection, testing, and maintenance protocols should be developed to confirm water supply systems are still adequate for the system design. As stated above, water supply systems change over time, and with them the availability and reliability of these systems also change. Typically, water-based fire protection systems are designed to function from a specific water supply system and that information is used for the life of the system. By developing new practices to ensure that the water supply for water-based fire protection systems is still adequate to ensure functionality of the designed system, the system can still be reliable and adequate.

Public messaging for water supply shortages often notes water saving methods in the domestic and commercial industries. Lawn watering regulations and similar water saving requirements are typically distributed to the public in times of water shortages. Water usage restrictions such as this are common in areas where drought conditions occur, such as Texas, California, and New Zealand. The addition of including messaging regarding water-based fire protection systems to these announcements would be helpful in informing the average citizen of the vast implications of water supply shortages and how it can relate to public safety.

Water supply shortages can be supplemented with other solutions for fire protection systems that involve non-water-based fire protection systems. Other types of systems should be further explored to determine if they can provide appropriate protection to the building or hazard if water supplies are deemed inadequate. Fire protection engineers can work with AHJ's to use these systems as primary or secondary for the facility.

Figure 18. Survey of Stakeholders that should be consulted.

Recommendations

As a result of the both the literature review and the survey, the following recommendations are suggested.

Policy changes

At the current time, there is very little information on policy changes as it impacts fire protection systems use of water supplies. Countries are beginning to feel the impact of climate change on water supply systems in general and some are beginning to enact legislature to help to prevent and prolong their current water supply systems to ensure availability. Some countries are also beginning to supplement their current water supplies with various other means to ensure that there will not be shortages in the future. The countries that are enacting these policies will have a much easier time when trying to protect their fire protection systems from a water supply shortage simply by means of protecting and enlarging their current water supply system infrastructure. This study has looked at a very limited sample size of countries that are actively preparing and protecting their water supply systems. The vast majority of communities across the world do not have any legislation to protect water supply systems in the event of climate changes or other natural disasters.

Education

Members of the fire protection community will have to begin to accommodate for possible water shortages in the design of their systems. This will have to be a twofold approach. Firstly, education is needed on how to identify areas that may be subject to water shortages in the future. Specialists will have to learn to recognize areas that may be subject to future water shortages. This can involve stakeholders, such as those referenced above, that may be better familiar with the area and its climate. The second portion is implementing solutions/alternatives on how to supplement fire protection systems when designing said systems. Adding elements of safety to ensure that the systems, whether they be sprinkler systems or fire department suppression teams, will be able to operate effectively even in the instance of a water shortage, will help to maintain these systems capability in combatting a fire emergency. The development of an education policy to verify that fire protection specialists have accounted for water supply shortages in the design and commissions of their systems should be implemented. Fire departments should also be educated about the possibilities of water shortages, even in areas where shortages may be considered unlikely, to ensure they have the proper controls in place to ensure an adequate and reliable water supply to combat fire emergencies.

Future Research

There are many avenues for future research to take place in regards to water supply shortages. Discovering the true impact of climate change on water supply systems is not fully known yet, but there are trends pointing to the fact that climate change is hurting the water supplies across the world. This in turn will reduce the amount of available water for fire protection systems, fire department response, and fire suppression.

Research into other options for fire protection systems outside of water-based systems is already being conducted, but special consideration should be given to furthering this research as the amount of water supply shortages grows yearly. Researching system level technology and the use of lower flow or pressure systems should be explored. Alternative solutions to upgrading water supply infrastructure would also be a reasonable avenue of research. There are many countries with desalinization facilities in place, so including these facilities in the water supply systems of regions, especially regions with easy access to ocean water, would be a major improvement on the availability and reliability of water supplies.

Working with urban planners on the process of developing policies around water shortages and including local fire protection engineers and other stakeholders in the policy. An easily understandable methodology to determine which regions are at risk for a water supply shortage should be developed for use by urban planners as well as the design and engineering community. Being able to determine quickly and relatively easily if a region may be subject to a water supply shortage will help fire protection engineers and other stakeholders when developing/designing their fire protection systems. This will ensure reliability and effectiveness of fire protection systems in a fire emergency during a water supply shortage scenario. This methodology can be developed similarly to earthquake zones. Using a risk-informed design methodology to determine water shortage zones and implementing control measures and / or redundancies into the water supply system would help in maintaining a reliable and adequate water supply system.

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APPENDICES

Appendix A

Question 17 Free Response Answers:

- Water Utilities are denying they are required to supply fire water efforts to the community networks they operate. Policy and poltical interfernce involved at all levles as no one wants to pay for upgrading 100 year old water syste,s yet 1.2 billion is spent on private fire water systems. Crazy.
- Our central water system work well 1000-1400 gpm hydrants. Ponds & river along with central water system location.
- Pleasae contacxt me for copies of bulletins I have written on these issues. Solutions to water supply issues vary from project to project.
- water standards or problems working from one set of standards for compatability of products
- In the Netherlands we use a lot of watertanks for sprinkler systems etc. We found these tanks to have a lot of corrosion after some years. The need to revise a tank or to replace it leeds to periods where the watersupply for the fireprotection systems in inadequate. We also sometimes use the citywaterpipes for sprinkler systems and these pipes are becoming smaller and smaller in diameter for a number of reasons so a supply that was sufficient years ago is in danger of becoming insufficient.
- lack of towns water for farm industries such as chicken farms and on-site industrial processes poses a challenge for fire fighting water supplies
- underwriters should have a great deal of information regarding utilities and failure rates.
- Designs taking suction from water retention ponds in regions that have subsequently experienced drought. Failure of Municipalities to maintain water systems - out of sight out of mind - until water fails to come out of a tap or a pipe break inconveniences people. This is much more wide spread than is indicated. Water quality well monitored. The absence of oversight on water authorities concerning pressure/volume testing issues as well as pro-actively communicating of those test results to stakeholders is rampant. Failure of Planning & Building oversight function to consider fire protection demands. The unrecognized or unmonitored impact of pressure/volume variations to the adequacy of hydraulically designed systems leads to a failure mode waiting to be revealed by a crisis. The sometimes over reliance of the capability of ESFR systems predicated

upon water systems with variability in pressure/volume as a function of the system operation or area development.

- Move towards water misting and water treatment with surfactants noted to be increasing in popularity.
- I am a Consultant Electrical , Mechanical , Civel Engineer . I work with witness expertise engineering, I do not work with water supply system
- Water supplies in the WUI have become a point of focus in the FPE community. As people are building further into rural areas, the infrastructure design is not keeping up.
- Lack of internal inspection of underground pipe per NFPA 25
- Also look at no running live hydrant flow test, but allowing computer models and modelling to determine fire flows and design perimeters
- In South Africa a new sprinkler systems will have its own private water storage and pump. Going back 30 years sprinkler system were municipal fed. Private hydrants typically still rely on municipal water supply and frequently encounter issues with supply
- The water utility providers immediately go to a reduction is pressure to prevent failing water piping ruptures and to decrease irrigation usage. They do not recognize the fire department or fire protection a one of their customer service obligations. This is a difficult mindset to change.
- None
- I have also been consulted on the flip side of this issue where a community expansion led to new/larger water mains and higher pressures which then exposed existing buildings with sprinkler systems to pressures in excess of the 175psi rating of many of the system components, invalidating the fire pump designs, and a long discussion on the pros/cons of pressure reducing valves.
- Drought and overbuilding in undersupplied locations in our state.
- N/A
- I work with water utilities across the US to meet building sprinkler system demand. The trend is decreasing flows and pressures resulting in an increased reliance on fire booster pumps and water storage tanks.
- I have not had experiences with climate issues causing fire water supply shortages. The issues I have had deal with increase development in an area causing once adequate flows and pressures to now be reduced to inadequate levels; this shows the importance of including a safety factor in all sprinkler system designs.
- TANKS AND PUMP FOR D SYSTEMS, WELLS AND RESIVOIRS FOR COMERCIL, SCHOOLS, MANUFATURING AND STORAGE
- none
- Perhaps the largest issue I have come to realize is that of folks correctly testing water supplies. The industry utilizes water supply testing procedures that are often misunderstood, arbitrarily modified (without technical understanding of key

hydraulic principles), and flat-out misused. I have encountered or been made aware of numerous examples of projects that have fallen into big problems due to inadequate water supply identified late in a projects' development or construction. Current test methods fail to account for a myriad of unknowns and make unsupported 'assumptions' regarding hydraulic conditions and/or out-of-sight infrastructure.

- The individual responsible for providing the water supply & not having the resources to fund the adequate water supply & nercessary pressures.
- Contaminated ground water destroying fire protection equipment.
- None.
- water department requirements to retrofit existing sprinkler systems with reduced pressure or other backflow prevention devices. Typically the water supply cannot provide sufficient pressure to make those changes.
- On Long Island, NY, chemical contamination of the aquifer is more likely, causing wells to be shutdown or filtration systems installed.
- Insufficient private water storage.
- Unable to use the "Other, please specify" answer on the "How has a water shortage event impacted Fire Department response and suppression efforts (select all that apply)?" question.
- MAINTENANCE ISSUES
- In the Dominican Republic all fixed water based fire suppression system's water supplies are private water tanks or reservoirs due to the city water supply be considered as unreliable. On most buildings/facilities the water supply is sized to the expected most demanding hazard, but no always. Water shortages can lead to water supplies' quantity be below minimum required.
- I have never had a water supply issue. Plenty of water here. Not an issue.
- Some of these H2O issues are already common with many rural / volunteer departments so water transfer and hauling techniques are being utilized. Interesting study on the NFPA water supply time basis and a possible revisit / revalidation - Grad student project?. Can the results of this study be provided to at lest the alumni network? Great and timely study issue.
- Part of our jurisdiction has a municipal water supply that is not adequate for even a 13D system. Through testing for a proposed development we learned that the current supply for the area that has two large mercantile occupancies and a 3 story hotel is inadequate to provide sprinkler and hose demand so we are requiring alternative water supplies for new construction to meet fire flow but still working through the hazard with the existing occupancies.
- I have designed FP systems for industry for 30 years and never had a water shortage problem.
- Texas has a minimum required pressure of 35 psi to be supplied by the municipality but the FP systems have been designed to the normal system

pressure of 65 psi. Utility suppliers think the 35 is all they have to provide. Not true.

- In the worst case I have seen, Old abandoned wells had to be put back into service to provide water for tankers/tenders and possibly engines.
- I work in >10 states, I see more infrastructure issues than anything.
- Have observed water wasted on fires that could not be extinguished and water was not needed for cooling. It only resulted in environmental impacts / contamination and water issues for the community. Water should only be used where it is beneficial and not just to spray on a fire that is not going anywhere. Let it burn. Talking about very large total loss warehouse type fires where it would have been beter to let it burn and protect exposures vs contaminating adjacent ground waters.
- Water supply deterioration is a potentially big problem that goes broadly ignored outside of providing a safety cushion. As an example, my company has had an increasing set of issues with a certain large client when it comes to available water supply. As the years have gone by the water supply on their property has become increasingly over-stressed. There is significant safety factor around water supplies and system requirements, but just as system density curves were revisited recently it could be reasonable to revisit flow test standards to consider if the standard practice needs updating.

Oklahoma State University Institutional Review Board

Date:	03/17/2022
Application Number:	IRB-22-122
Proposal Title:	Water Supply and Climate Change: The Impact of Water Stress on Fire Protection Systems
Principal Investigator:	Virginia Charter
Co-Investigator(s):	
Faculty Adviser:	
Project Coordinator:	
Research Assistant(s):	Justin Fletcher
Processed as:	Exempt
Exempt Category:	

Status Recommended by Reviewer(s): Approved

The IRB application referenced above has been approved. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in 45CFR46.

This study meets criteria in the Revised Common Rule, as well as, one or more of the circumstances for which continuing review is not required. As Principal Investigator of this research, you will be required to submit a status report to the IRB triennially.

The final versions of any recruitment, consent and assent documents bearing the IRB approval stamp are available for download from IRBManager. These are the versions that must be used during the study.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be approved by the IRB. Protocol modifications requiring approval may include changes to the title, PI, adviser, other research personnel, funding status or sponsor, subject population composition or size, recruitment, inclusion/exclusion criteria, research site, research procedures and consent/assent process or forms.
2. Submit a request for continuation if the study extends beyond the approval period. This continuation must receive IRB review and approval before the research can continue.
3. Report any unanticipated and/or adverse events to the IRB Office promptly.
4. Notify the IRB office when your research project is complete or when you are no longer affiliated with Oklahoma State University.

Please note that approved protocols are subject to monitoring by the IRB and that the IRB office has the authority to inspect research records associated with this protocol at any time. If you have questions about the IRB procedures or need any assistance from the Board, please contact the IRB Office at 405-744-3377 or irb@okstate.edu.

Sincerely,

Oklahoma State University IRB

VITA

JUSTIN FLETCHER

Candidate for the Degree of

Master of Science

Thesis: WATER SUPPLY AND CLIMATE CHANGE: THE IMPACT OF WATER STRESS ON FIRE PROTECTION SYSTEMS

Major Field: Fire Safety and Explosion Protection

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Education:

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Completed the requirements for the Bachelor of Science of Fire Protection and Safety Engineering Technology at Oklahoma State University, Stillwater, Oklahoma in July 2017.

Experience:

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Professional Memberships:

SFPE, NFPA TxFPA