Unfiltered Drinking Water Systems in Oregon: Resilience to Climate Change

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1. Background

Climate change is altering the way that humans have traditionally planned for the future. Policies, infrastructure and management that will be affected by climate change can no longer be planned assuming an unchanging future. Instead of preparing for a certain future, new policies, infrastructure and management needs to be created with the ability to adapt to a variety of situations in the future. Not only this, but historical infrastructure and policy needs to be re-evaluated to ensure that it will continue to serve its purpose in the uncertain future. The impacts of climate change will be far reaching, affecting socio-ecological systems across the globe at various scales. It is therefore crucial that managers of socio-ecological systems begin implementing change in policy to make our systems more resilient to climate change.

1.1 Resilience

The idea of resilience plays a key role in understanding how to prepare for climate change and lessen vulnerability globally. Climate change predictions are undeniably uncertain; although many models have improved dramatically over the past decade, the International Panel for Climate Change (IPCC) models still have different predictions for the various climate models and emissions scenarios that are possible (IPCC, 2014). At this point in time many places have already begun to feel the impacts of climate change, but scientists are still unsure about the extent of the changes we are going to see: how much change will occur is dependent on current and future emissions, as well as positive feedback loops. Because of this, systems that are going to be impacted by climate change need to be able to handle a variety of climate scenarios. Resilience, which describes a systems capacity to absorb shock and still function differs from “stability” in that it doesn’t require the system to predict future events (Holling 1973). Instead, Holling explains how the resilience framework only requires a “qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take" (Holling, 1973). The resilience framework therefore is highly important in addressing the uncertainties of climate change that will impact global systems, and in helping humans to design systems that can respond to various uncertainties in the future.

Water systems are expected to be particularly vulnerable to climate change because changes in precipitation, temperature, the Snow Water Equivalent (SWE) and timing of snowmelt will alter the hydrological systems. The assumptions that historical water systems were built on play a key role in their resilience - or lack of resilience -to future climate changes. Most water systems have three different levels of resilience; engineering, ecological and social. While engineering resilience simply describes a systems ability to return to a stable state after a perturbation, Carl Folk claims that social-ecological systems are forms of complex adaptive systems in which each recovery trajectory is unique, with "feedbacks among multiple scales that allow these systems to self-organize" (Folke, 2006). Folk argues that these complex adaptive systems do not simply return to the same state after the disturbance, but rather the "disturbance has the potential to create opportunity for doing new things, for innovation and for development" (Folke, 2006). Social-ecological resilience is key to understanding water systems because it is used in the context of an integrated system feedback (Folke, 2006). Water systems are a perfect example of a social-ecological system because humans rely heavily on water resources, but water systems themselves are impacted by humans through ecosystem and landscape alteration, as well as through human induced climate change. However, most water systems have historically been controlled in a way that assumes an unchanging climate. These assumptions are built into water law and water rights policies, into the infrastructure that provides us with flood control, electricity and drinking water, and into the way we manage land and produce food.

Becoming more resilient isn't just about technological resilience to environmental issues; building more dams, reservoirs, and desalinization plants cannot make our water systems completely resilient to climate change on their own. As Bennet et al. (2016) points out, the ways that we currently manage “Water-Energy-Food” systems are inefficient, with money spent on technology and infrastructure to increase the resilience of our water systems to water issues caused by agriculture, without even looking at what he calls “natural infrastructure” based solutions. Instead, Bennet et al. suggests that managers of water, energy and food systems to work together on “landscape-based approaches to manage water–energy–food (W– E–F) nexus risks and trade-offs”, which would not only be more effective, but also cheaper than managing these systems with the assumption that they are not connected (Bennet et al., 2016). Gober et al. (2015) describe the problematic nature of this relationship, giving the example of “the governance gap between land use planning and water management in the USA where land planners decide the pace and form of future development, with the water sector responding to changing development patterns” (Gober et al., 2015). In addition, the conservation policies we have in place today assume unchanging climate, and will no longer be effective in the coming years; instead new policies are needed that focus on future adaptation rather than sustained management (Gober et al., 2015). Because addressing land use might be one of the easiest ways that we can improve resilience to water supply and quality issues, it should have a bigger part in discussions about how to make water systems more resilient. In this study, I evaluate the resilience of unfiltered drinking water systems in Oregon, in regard to water quality risks associated with climate change by identifying contamination risk in each watershed, graphing correlations between water quality and weather parameters, assessing the hydrologic conditions leading up to a cryptosporidium event in Portland’s source water, and completing an economic analysis on the feasibility of installing filtration plants. My findings suggest that larger systems will need to rely on technological resilience in the future, while smaller systems may need to resort to resilience through land management.

1.2 Water Quality Issues

While much of the research on climate change addresses how it is expected to impact global water supply, relatively little has focused on how climate change could impact water quality (Bates et al., 2008, Vörösmarty et al., 2000). This is not because climate change will not have an impact on water quality, but rather because the changes are often mixed in with and obscured by land use impacts. Although many researchers have said that climate induced water quality changes will be very minimal compared to land use impacts on water quality, Murdoch et al. (2000) argues that “climate stress would increase the frequency with which ecosystem thresholds are exceeded and thus lead to chronic water-quality change”, and that this is an issue we need to be paying attention to. Rather than simply altering the inputs that go into the water, climate change can alter the aquatic and terrestrial ecosystems that allow our water systems to function properly. Very few have looked into the impacts on water quality, and specifically water quality for drinking water purposes. This is important because we need to start making systems resilient right now, through policy and technology, in order mitigate the effects of climate change.

Water systems all over the world face vastly different water quality issues, but many surface water systems have similar concerns. Water quality issues for surface water systems can be divided into three groups; microbial aspects, chemical aspects and radiological aspects (World Health Organization, 2003). Chemical parameters include pH, turbidity, dissolved oxygen and nitrate; which all differ depending on the characteristics of the watershed. Microbial aspects include bacteria, viruses and parasites, and are the most common health risk associated with drinking water (World Health Organization, 2003).

Temperature, which doesn’t fit into either of these categories, still impacts water quality to the extent that heat has been identified in the Clean Water Act as a pollutant. While temperature might be the only water quality parameter directly affected by climate change, all of the other parameters have the potential to be affected as well through the delicate biogeochemical relationships that connect various parts of water systems. For example, an increase in temperature leads to a decrease in dissolved oxygen, which in extreme cases can lead to an oxygen deprived ecosystem that is uninhabitable by aquatic creatures (Whitehead et al.,2009). Excess nitrate in a system that often comes from agricultural runoff, can cause eutrophication, one of the most widespread water quality issues, which results in decreased dissolved oxygen and death of aquatic life (Compton et al., 2011). Turbidity, which is a measurement of the cloudiness of water caused by suspended particles, tends to be higher in systems that have more sediment runoff during rain events (Foley et al., 2005). Turbidity levels depend greatly upon land use in each watershed; activities like agriculture which alter soil structure can increase sedimentation during rainfall events (Foley et al., 2005). Bacteria levels in water system are affected mostly by the surrounding landscape; during rainfall events, harmful bacteria from human or animal waste can be washed into the water, creating a health hazard for humans (World Health Organization, 2003). However, growth rates of algae, and the production of nitrate from nitrifying bacteria, both potential water quality issues, can also increase or decrease, depending on temperature. Because most water quality parameters are interdependent, it is important to closely examine all relationships when analyzing impacts of climate or land use change.

1.3 How Climate Change and Land Use Impact Drinking Water

Different regions across the globe will be impacted in different ways by climate change; although regional patterns are hard to predict, it is likely that high latitude and the equatorial Pacific Ocean will experience an increase in yearly precipitation, while mid latitude sub-tropical dry regions will expect a decrease in yearly precipitation (IPCC, 2013). These changes in temperature in precipitation patterns will have a large impact on water supply issues, but also have serious implications for water quality. Several studies that examined the effects of increased precipitation and storm intensity on water quality found that this change led to an increase in sedimentation (Kistemann et al., 2002, Goransson et al., 2013). In addition, increased rainfall levels could lead to an increase in the levels of bacteria that are washed into a system (total coliform), an increase formation rate of Disinfectant by

Products (DBPs) in drinking water systems, and increased nutrient loading depending on landscape (Delpla et al., 2009, Whitehead et al., 2009). It is not only increased total rainfall, but increased storm intensity that is especially problematic for water quality; Curriero et al. (2001) finds that 68% of waterborne disease outbreaks in the United States from 1948-1994 were preceded by extreme precipitation events (above the 80th percentile). Bacteria and DBP's both increase health risks for humans whose supply comes from these water sources, while increased nutrient loading can have harmful impacts on ecosystems by creating algal blooms which lead to eutrophication. In addition, places which are expected to see an increase in temperature might expect an increase in bacteria and algae growth rates, and in nitrification – the process of bacteria producing nitrate- in drinking water systems (Delpla et al., 2009, Whitehead et al., 2009). For drinking water systems, an increase in bacteria could cause water systems managers to increase disinfectant levels within the system. While this could decrease risk of microbial contamination, it could also lead to increased levels of DBP's in drinking water supplies. Lastly, one of the biggest issues that may impact water quality is, in fact, a change in water supply – particularly in areas that are predicted to have a decrease in supply.

Areas that already have low annual precipitation are at risk for low water supply, as are those that have an unequal distribution of their annual precipitation. This is especially true for areas that rely on the slow release of melting snowpack for a cold-water supply during the summer, as climate perturbations are expected to decrease annual snowpack levels at lower elevations, and alter the timing of peak streamflow in places like the Pacific Northwest (Sproles et al., 2013, Farley et al., 2011). The predicted decrease in snowpack and change in timing could be especially problematic for Mediterranean climates like the Pacific Northwest of the United States, where there is a large amount of yearly rainfall, but where most the rain falls during the winter season. During dry, hot summers, limited water is shared by multiple stakeholders who struggle to meet their water needs. Areas that are prone to droughts may face increased rates of summer wildfires, which threaten surface water supplies

(Dalton et al., 2017). For many areas in the world, climate change is expected to increase annual rainfall, but this is especially problematic in the Pacific Northwest which is expected to have increased levels of precipitation and storm intensity in the winter, but drier and warmer summers, exacerbating both of the weather parameters that lead to poor water quality (Institute for Water, 2012). Because of this, analyses are needed for regional or small scale impacts of climate change on specific water supplies, so that water supply managers of habitat and ecosystems, agriculture, hydropower, industry, and drinking water can all begin to plan ways to make water systems more resilient.

As noted earlier, climate change is expected to impact water quality, but on a smaller scale than other issues like land use (Murdoch et al., 2000). However, certain water systems might be more susceptible to small climate perturbations than others. Aquatic ecosystems have been impacted globally with a variety of pollutants, from agricultural runoff to pharmaceuticals to waste water, but these systems still have higher (legally) accepted water quality thresholds for pollution than systems that humans rely on for drinking water (Findlay, 2009). In the United States, drinking water standards, set by the EPA through the Safe Water Drinking Act of 1974, has much stricter standards that those set by the Clean Water Act of 1972 which attempts to manage water quality in national water bodies by limiting point source pollution (not including runoff) (United States, 2003). Because drinking water standards are much stricter, it is much easier for a change in climate to introduce levels of pollutants that exceed drinking water quality standards. And, while most systems can simply remove the excess pollution that climate change might introduce through filtration, some systems do not have the ability to do this.

In the United States, some of the biggest water systems in the country - New York, Boston, San Francisco, Seattle, Tacoma and Portland - as well as many small-scale systems - are all unfiltered drinking water systems. Being unfiltered is not the same thing as being untreated – all of these systems add some form of disinfectant (usually chlorine) as well as other chemicals that maintain their water quality to the Environmental Protection Agency’s (EPA) drinking water standards. However, when their system does have a water quality event, which could consist of high turbidity levels from a landslide, cryptosporidium (bacteria) in the water supply, or high algae levels during warm summers, they cannot remove the pollutant. Because of this, unfiltered drinking water systems lack the technological resilience that most drinking water systems have to climate change, and are more susceptible to small shifts in temperature and precipitation. These major unfiltered systems have received exemptions to the EPA's filtration rule, because they have been able to show that the management of the watershed leads to minimal water quality risks. This has allowed cities, and therefore taxpayers, to avoid the major costs of implementing a filtration system. My research on the impacts of climate change on unfiltered drinking water systems shows that it is time for most large unfiltered drinking water systems to start planning for the costs and implementation of a filtration system; the impacts of climate change in the Pacific Northwest will have enough of an impact on water quality to make the costs of implementing a filtration system for larger providers worth the benefits of increasing resilience to climate change.

1. Situated Context

2.1 Climate and Water in the Pacific Northwest

In the Pacific Northwest, detailed climate model predictions have differed from what global models have predicted. Salathe et al (2008) attributes this to the inability of large scale models to capture large variations within small regions. In particular, the more detailed models show significantly more warming for the Cascade mountain range due to snow-albedo feedback loops that the large-scale models don't necessarily capture (Salathe et al., 2008). Because of increases in temperature, springtime snowpack in the Cascades will decrease, especially in areas 1800 meters and below (Mote, 2003). This decrease in the Snow Water Equivalent (SWE) is arguably the biggest impact that climate change will have on water resources in the Pacific Northwest; many water resource stakeholders rely on the slow release of melted snow from the cascades during summer, when there is relatively little precipitation

(Mote, 2003). Areas that do not receive runoff from snowmelt are also expected to have reduced summer flows: Praskievicz and Heejun (2011) find that in the Tualatin river basin, just outside of Portland, there will be a 37% decrease in summer streamflow, and a 10% increase in winter streamflow on average by 2070 due to climate change and urban development. However, these decreases are only amplified in rivers that normally receive snowmelt runoff; Chang and Jung (2010) find that models predict a decrease in snowmelt of 75% by 2080 in the upper McKenzie River basin. Not only do these extreme decreases in summertime streamflow pose a serious threat to agriculture, industries and drinking water municipalities who rely heavily on water during the summer, but the wintertime increases in streamflow could have water quality consequences such as sediment and nutrient loading (Praskievicz and Heejun, 2011).

The Pacific Northwest has always had a bi-modal climate, with cold wet winters and dry hot summers; this contrast is expected to increase in the future. Climate models have predicted that in the Pacific Northwest, temperatures will increase on an average by 2-7 ˚F by the 2050's. Although precipitation trends are more difficult to predict, scientists have found that there will be a slight increase in yearly precipitation, with increased frequency of extreme precipitation events, but drier summers than what is currently experienced (Dalton et al., 2017). Winter precipitation levels in the Pacific Northwest are expected to increase by 4.9 to 7.9% by 2050 and from 7.3 to 14.5% by 2080 (Dalton et al., 2017). While the Pacific Northwest receives, and will continue to receive, a high level of annual precipitation, the uneven yearly distribution of this precipitation could cause issues for many of the stakeholders who are dependent on water systems. During the hot dry summers, water is needed by many stakeholders; industries, hydropower generators, agriculture, and household consumers make up some of the biggest consumers of water, leaving little cold water left to protect habitat for species like salmon (Moore et al., 1996). While the first three stakeholders are mainly concerned with how climate change will affect water supply, municipal water providers are worried about how climate change will affect not only supply during the summer, but how warmer summers and rainier winters will impact water quality.

While many systems will be able to adjust their treatment processes and remove unwanted constituents through their filtration systems, water suppliers who do not have filtration systems in place will have a harder time countering these problems. In the Pacific Northwest, Seattle, Tacoma and Portland are all exempt from the EPA's Surface Water Treatment Rule filtration requirements. This is because they have been able to prove that the risks of water quality contamination are low enough that they do not need filtration; Portland's water system for example is in a protected forest with no public access other than through carefully guided tours. For most unfiltered drinking water systems, the forest essentially acts as a buffer to the water supply. Roots from the trees help create soil structure that allows the soil to retain moisture during the summer, and which holds the soil more firmly in place so that it isn't washed into the water supply during heavy rainfall events. In addition, forest shading of tributaries to the water source, and to the ground where water is retained in the soil, keeps water cool during hot and dry summer months. In the state of Oregon, there are three unfiltered water systems that all have different climates, population sizes, and water quality threats. However, all three of them are going to need to make decisions in the coming years about how to make their systems more resilient to climate change, and installing filtration systems may be the most effective, though not the cheapest, method of doing so.

2.2 Oregon's Unfiltered Drinking Water Systems

While all three of the unfiltered drinking water systems in Oregon have forested watersheds, all three face different water quality threats.

The smallest unfiltered drinking water system in Oregon is in Reedsport, Oregon, located about halfway up the coast (Figure 1). The City of Reedsport provides water to around 4,000 customers from the 310-acre Clear Lake water source which can hold up to 16, 600 acre feet of water (3,200 of which is considered usable). Clear lake exists in the basin of the ancestral Clear Creek headwaters which were damned by sand-dune encroachment (U.S. Department of the Interior, 1980). The entire basin was logged in 1940's and now consists of second growth forest, of which smaller sections have been logged since (U.S. Department of the Interior, 1980). The lake itself gets 70% of its annual water supply from small creeks and runoff within the watershed as well as ground water inflow, while the other 30% comes from precipitation directly into the lake. Reedsport has a temperate marine climate with average temperatures currently ranging from 43˚C-60˚C, and average annual precipitation of 72 inches, with 70% falling November-March. During all but the winter months, the lake remains stratified, with warmer water sitting on top of cold water. A 1980 USGS survey of water quality in the lake found that while suspended sediment sampled from inflows correlated to precipitation (increased with precipitation), there was no noticeable correlation in the lake – they attribute this to the fact that suspended sediments in the streams flowing into the lake are deposited in heavily vegetated swamps (U.S. Department of the Interior, 1980).

Currently, Clear Lake is surrounded by a 2.2 square-mile designated drinking water protection area, visible in Figure 1, which is mostly forested but half of which is bordered by the Oregon Coast Highway 101 (DEQ, 2003). Although there is no commercial activity in this designated drinking water protection area, and city code bans many activities in the watershed that could threaten the source water, private landowners in the watershed are still allowed to log and to spray herbicide to ensure successful tree growth. Recently there has been controversy over the application of herbicide (by helicopter) so close to the drinking water supply, bringing into light the difficulties that might arise when watersheds are managed by a variety of stakeholders (Jordan-Cascade, 2013).

The second largest unfiltered drinking water system in Oregon is in Baker City, which is in the northeast corner of Oregon (Figure 1). This surface water supply has intakes from 7 different streams in the Elkhorn Mountains, located in the Powder Subbasin, including Elk Creek, Goodrich Creek, Little Marble Creek, Little Mill Creek, Little Salmon Creek, Mill Creek and Salmon Creek, as well as from Goodrich reservoir which is formed by Goodrich Dam. The climate in the Powder Subbasin differs greatly from that in Reedsport and Portland's watersheds; the rock creek weather stations gets only 20.8 inches of yearly precipitation on average, with hot and dry summers (DEQ, 2003). The various intakes in the Elkhorn Mountains are located at about 5,000 feet of elevation (DEQ, 2013). The 2013 Powder Basin Status Report and Action Plan (SRAP) notes several types of land change that can negatively impact watershed health and water quality, which include invasive species which decrease the coverage of subalpine fir and white bark pine, soil erosion caused by livestock grazing and a high rate of landslides (DEQ, 2013). Currently 75% of forested land in the Powder river subbasin is grazed by livestock that alter the riparian vegetation around rivers and streams which can act as a buffer to the water source (DEQ, 2013). The Powder Subbasin has a long history of mining which peaked during the years of 1896-1908; but which has caused significant impacts to the watershed; during this time period many trees were harvested, stream channels were altered and mill tailings were discharged into streams (DEQ, 2013). In the 2003 Source Water Assessment Report, the entire "drinking water protection area" was marked as a sensitive area, due to the high soil erosion potential identified (especially close to the intake) as well as soils with high runoff potential (DEQ, 2003).

The land in the Baker City watershed is primarily managed by the U.S. Forest Service, and has had a history of logging, with logging still taking place in the watershed, close to several intake structures (DEQ, 2003). In 2013, Baker City had a widespread cryptosporidium (pathogen) outbreak, triggering the implementation of a UV treatment plant in Baker City, which kills microbial contaminants like cryptosporidium. Although Baker City is still unsure what the source was for the contamination, many believe it to be caused by cattle grazing in the Elk Creek Drainage Area; in 2016 Baker City Applied for funding to construct and reinforce fences surrounding the watershed, to keep cattle from wandering out of their permitted grazing areas.

Portland, OR and surrounding towns receive water from the Bull Run reservoir source, located in the Mt. Hood National Forest. Bull Run has served as Portland's primary drinking water supply since 1895, and has remained closed to the public since 1904 to protect against the introduction of contaminants into the source water, and decrease the risk of a forest fire which could would render the water source unusable for a long period of time (USDA, 2007). Throughout the 1900's the United States Forest Service and the City of Portland fought over logging in the watershed, and the threats that it posed to water quality. Because of this, it wasn't until 1993 that logging was ultimately ended in the Bull Run watershed, after 22% of the watershed had been logged (USDA, 2007). While 12% of the watershed has slopes of 50% or greater, only 1.7% of the watershed has been rated as high hazard for shallow or deep-seated landslides (City of Portland Water Bureau, 2006). Precipitation varies greatly throughout the watershed due to differences in elevation (ranging from 755 ft. to 4,750 ft.); lower elevations receive 81 inches of yearly precipitation on average, while higher elevations receive up to 170 inches per year (City of Portland Water Bureau, 2006). The watershed is primarily evergreen conifer forest, dominated by Douglas fir, western hemlock, western red cedar, Pacific silver fir, and noble fir (City of Portland Water Bureau, 2006).

The Bull Run water source is composed of two reservoirs, created by dams on the Bull Run river; the reservoirs are located at the head of the river and receive runoff from the surrounding watershed. Because of the watershed's geography, none of the water entering Bull Run comes from snowmelt runoff during the summer. The Portland Water Bureau serves 950,000 customers through direct supply and wholesale. Portland, unlike the two previous watersheds, has had a variance on cryptosporidium treatment (meaning that they are not required to treat drinking water for cryptosporidium) and an entire section in the water quality department that is devoted to sampling frequently to ensure a cryptosporidium outbreak doesn’t happen in Portland. Recently however (3 times during January 2017) cryptosporidium has been found in the source water, leading people to question Portland’s exemption from treatment.

Bend, OR, which is located in Central Oregon east of the Cascade mountain range and installed a membrane filtration in 2016, provides and interesting comparison study for the other unfiltered water systems in Oregon. Bend, whose water comes from Bridge Creek in the Deschutes National Forest, decided to install some type of filtration plant in 2013, after the cryptosporidium outbreak in Baker City. Bend had been contemplating how to comply with the EPA’s Long Term 2 Enhanced Surface Water Treatment Rule (LT2) which required them to install a treatment plant for the microbial pathogen Cryptosporidium. However, rather than installing a UV “filtration” system like Baker City did, Bend decided to install a $30 million membrane filtration plant, which can remove sediment from the water, as well as microbes (Borrud, 2013). This filtration system greatly decreases Bend’s risk to events like forest fires in the Deschutes National Forest, which could render the water source unusable without a way to remove the ash.

It is important to note, that all surface water systems are required to have a backup groundwater source. Each of the above water sources has a backup groundwater source that is used when the main water source needs to be shut off in case of a water quality event, or simply to supplement the main water source when levels are running low. This greatly increases resilience to short term events, but can only provide an alternative source once water providers have realized the main source needs to be shut off. Backup sources will provide water to customers eventually, for a short amount of time, but only will only be effective if water providers are able to quickly eliminate the water quality contamination from the system.

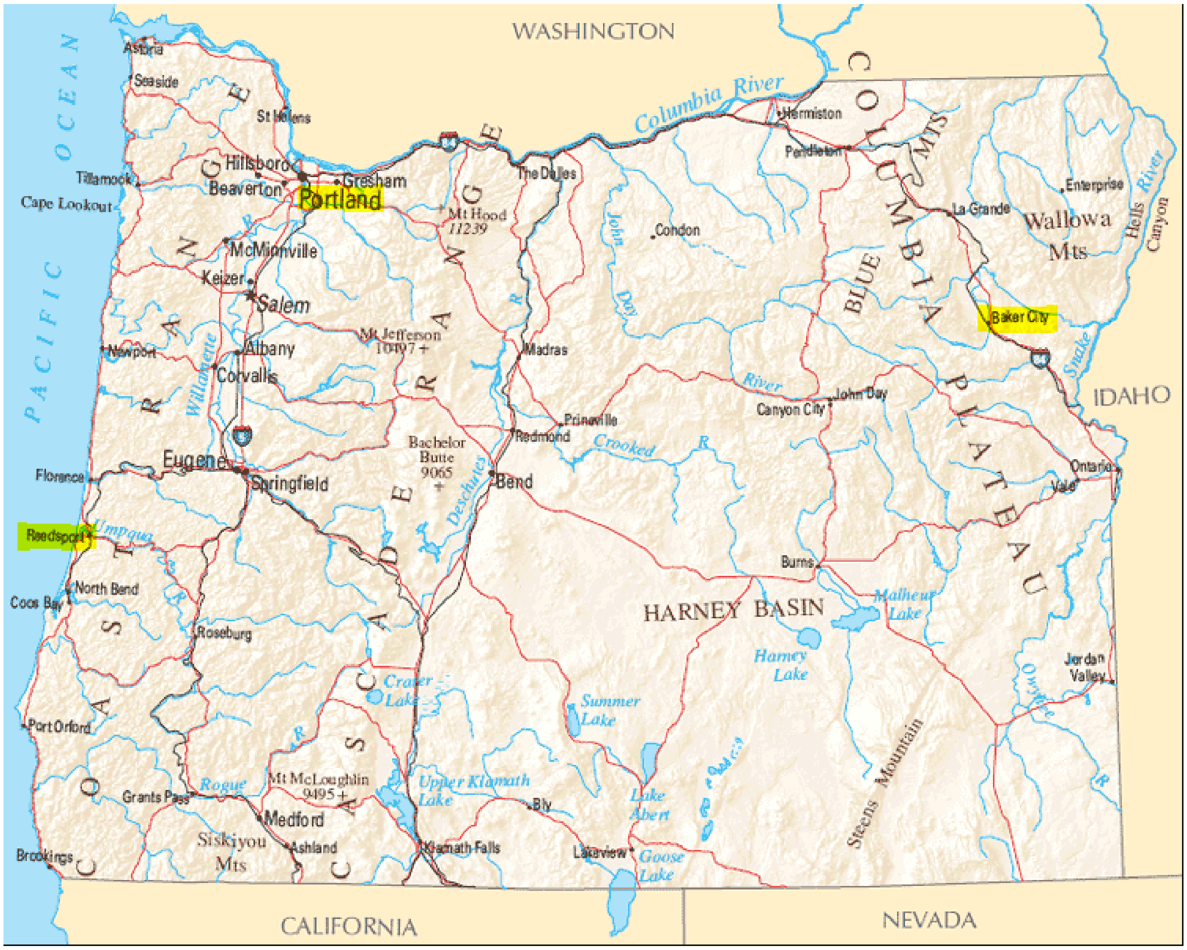

Figure 1. A map Oregon, with the 3 unfiltered drinking water systems highlighted.

3 Methods

To understand how climate change might impact water quality in the future, I identified the water quality risks for each of the three unfiltered water systems in Oregon based on each watershed's individual characteristics, analyzed the relationships between weather events and the specific water quality risks, and evaluated what types of resilience would be financially feasible for each water system.

3.1 Source Water Assessments

I began by using the Department of Environmental Quality (DEQ) Source Water Assessment reports that were completed for all Oregon surface water drinking systems from 2002-2004. Each of these reports include maps which delineate the source water, the source water protection area, and the potential threats to the water supply as “possible points of contamination”. I then noted the potential impacts of each of these potential threats that could be exacerbated by climate change for further analysis. For example, risks of chemical spills on highway 101 in the Clear Lake watershed was not graphed against weather parameters because climate changes wouldn’t increase the likelihood of a chemical spill happening; on the other hand, risk of sedimentation from logging sites within the watershed were included for further analysis because levels of turbidity are expected to increase with climate change.

3.2 Correlations between Water Quality and Weather Parameters

The goal of these graphs was to show possible correlations between water quality parameters and weather patterns in the Portland, Reedsport and Baker City watersheds. For example, watersheds that were at risk for turbidity events, such as Baker City and Reedsport, were analyzed using correlations between total daily precipitation and turbidity levels over the course of several years. For the Bull Run water supply, turbidity was plotted against precipitation as a proxy for the likelihood of a pathogen being in the water, since the number of actual pathogen findings in the watershed are so few. DBP’s are expected to increase with turbidity due to the influence of organic matter on trihalomethanes (Delpla et al., 2009), and therefore graphs of DBP’s versus precipitation were also created for the watersheds that have turbidity listed as a potential impact. Drinking water data used was that published on the Oregon Health Association Drinking Water Data Online database, which publishes daily averages or totals of many water quality parameters in a system (OHA 2017).

3.2.1 Hydrologic Analysis for Bull Run Watershed

Tributaries to source water reservoirs that are not “flashy” (meaning the surrounding drainage area has a relatively high infiltration capacity) might not show direct correlations between precipitation and turbidity. In watersheds that are mostly forested, precipitation will be infiltrated until the soil becomes saturated (the point at which this happens varies depending on soil type and depth) at which point the surface runoff will begin to occur. It is at this point that we would expect to see precipitation impacting the turbidity of the water. Since Bull Run watershed is the only unfiltered drinking water system in Oregon that doesn't currently have plans to implement a treatment system, it will have the greatest future risk for bacteria or pathogens contaminating the water supply. To better understand the relationship between precipitation and runoff in these forested watersheds, I performed a hydrologic analysis on the storms preceding the cryptosporidium findings in the Bull Run watershed in January and February 2017.

I first performed a hydrograph separation analysis on for the South Fork tributary to Bull Run on the storm that occurred from December 27th - December 28th. The hydrograph separation analysis allows the user to subtract the basin-averaged storm runoff depth from the basin averaged storm precipitation, to get an infiltration rate for the surrounding watershed. This calculation assumes that the infiltration rate is equal in all parts of the basin, when in reality there are most likely pockets of saturation that occur. I then created an antecedent moisture index, to calculate how much moisture was in the soil before the storm on December 27th, and how this may have impacted the infiltration rate during the December 27th storm. The antecedent moisture index was created using a 30-day exponential decay calculation, that uses rainfall data for each day, along with the available water capacity of the soil and the soil depth, which in the Bull Run watershed is 0.2 and 60 inches respectively (U.S. Department of the Interior, 1996). Results from the hydrograph separation and antecedent moisture index are then compared to future precipitation trends in the Pacific Northwest to determine how frequently we could expect to see conditions like this, which could have led to the cryptosporidium presence, in the future.

3.3 Filtration System Cost Analysis

In 2016, the City of Bend implemented a membrane filtration system to their surface water system, removing themselves from the list of unfiltered drinking water systems in Oregon. This was in response to the EPA's Long Term to Enhanced Surface Water Rule update in 2011 which required unfiltered drinking water systems to implement treatment for the deadly pathogen cryptosporidium which occurs in animal feces. Bend debated for several years over several treatment methods for cryptosporidium, and at last decided on membrane filtration. Baker City on the other hand, decided to implement an Ultraviolet Light system, which is much cheaper than a membrane filtration system. Reedsport, which had been using ozone to treat for cryptosporidium made the decision in February 2017 to change to a UV treatment system, while Portland maintains a variance from the EPA, meaning they do not have to treat for cryptosporidium.

Using the City of Bend as an example, I looked at current water rates for each of the four cities, and calculated how much water rates would need to increase in order to pay for a membrane filtration system. I then compared the rate increases to median income data for each of the water provider's cities, and discuss whether or not customers would be able to afford water rate increases. Finally, I discuss why the cities might have chosen the treatment that they did, and what the best future options might be for each of them.

4. Results

4.1 Source Water Assessment Reports

The Department of Environmental Quality souce water assessments were created for all surface water drinking systems in Oregon, in 2003 . These Source Water Assessment reports gathered data from watershed visits, interviews and observations to identify possible water qualtiy threats within the watershed. Table 1 below summarizes the findings for each of the unfiltered drinking water systems in Oregon, noting their potential water quality impacts. Figure 2 shows a map of Reedsport's source water, Clear Lake, with the source water protection area outlined in black and the potential threats marked by pink points; many of the potential threats for Clear Lake come from the clear cutting and timber harvest that was taking place during the watershed in 2002 (DEQ Reedsport, 2003). While the number of sites has dwindled, timber harvest still takes place in the watershed today, and the risk of hazardous material spills from highway 101 still exists. In February 2017 Reedsport's public works office decided to replace their current ozone treatment plant with a UV treatment system, which in the future will minimize the risk of microbial contaminants that may be washed into the watershed during storm events. The UV treatment plant, however, will not be able to remove harmful toxins that can be produced by the algae blooms that frequently occur in the stratified lake - most likely from excess nutrients washed in through runoff.

Table 1. Summary table of DEQ Source Water Assessment identified potential contamination sources for each of the three unfiltered water systems in Oregon.

Water System	Potential Contaminant Source Type	Number of Locations	Potential Water Quality Impacts
Baker City	Goodrich Dam	1	Turbidity
Baker City	Timber Harvest	4	Turbidity and Nitrates
Reedsport	Coast Highway	1	Turbidity, fuel or hazardous materials (spills or leaks)
Reedsport	Water Treatment Plant	1	Treatment Chemicals
Reedsport	Clear Cuts	1	Turbidity and Nitrates
Reedsport	Transmission Line Maintenance	1	Turbidity
Reedsport	Alage Growth	1	Algae Blooms
Reedsport	Logging Site	1	Turbidity and Nitrates
Portland	Warm-blooded wildlife species	1	Microbial contaminants

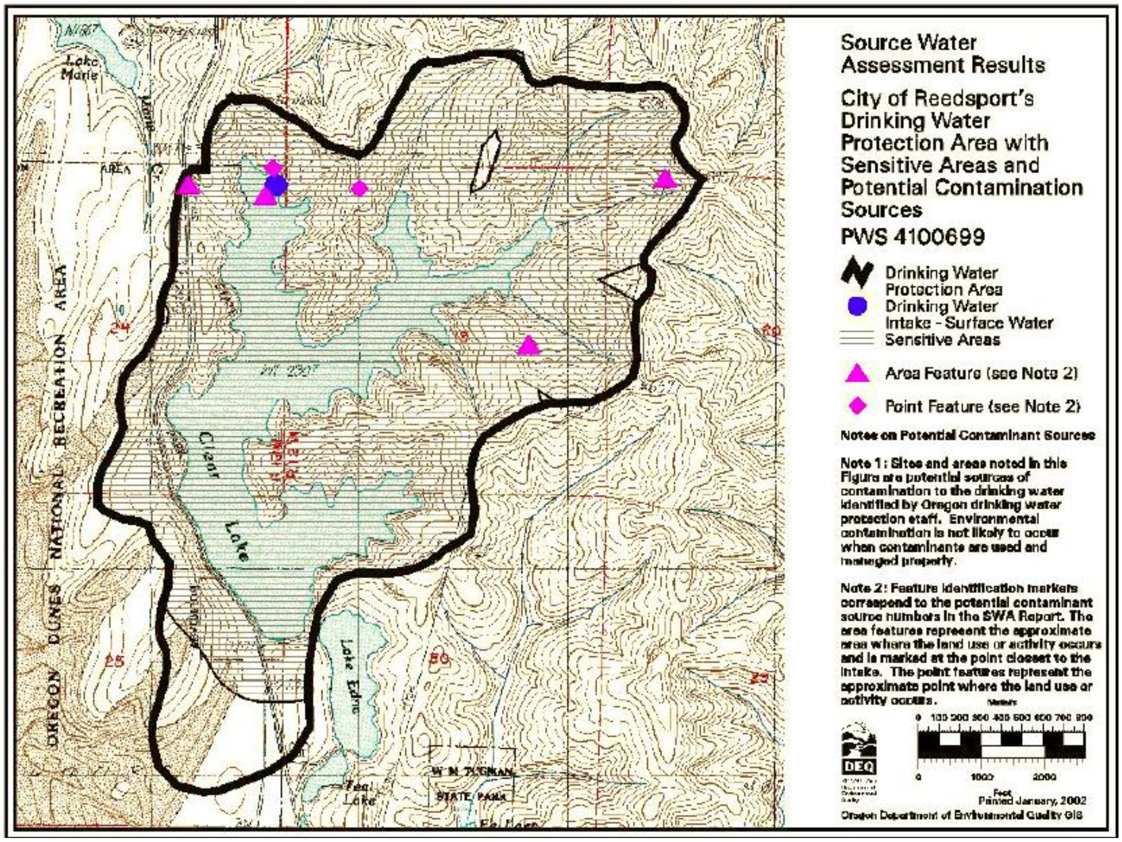

Figure 2. Map found in DEQ assessment report of Reedsport's drinking water source (Clear Lake) outlining the source water protection area, and marking potential contamination source sites.

Baker City's main identified source water threat was, like Reedsport's, timber harvest in the watershed, which can impact runoff, leading to possible increases in turbidity and nitrates. In addition, the DEQ listed Goodrich Dam as a possible point of contamination as well, due to fluctuation levels in the dam that could increase erosion and turbidity in the drinking water source. The DEQ map (Figure 3) also shows that almost the entire protected area is considered "sensitive areas", which means that they are close to the source water and have high soil erosion potential or high runoff potential (DEQ, 2003). One important thing to note is that the DEQ report failed to discuss the risk of contamination from cattle grazing near the watershed. While cattle aren't supposed to be grazing in the watershed, after the cryptosporidium outbreak in Baker City in 2013, the city identified many locations in which the fences that were supposed to keep cattle out of the watershed were broken or did not exist. Since the implementation of a UV filtration system, cryptosporidium is no longer a risk within the watershed, but turbidity events from runoff in the sensitive areas surrounding the source water still are.

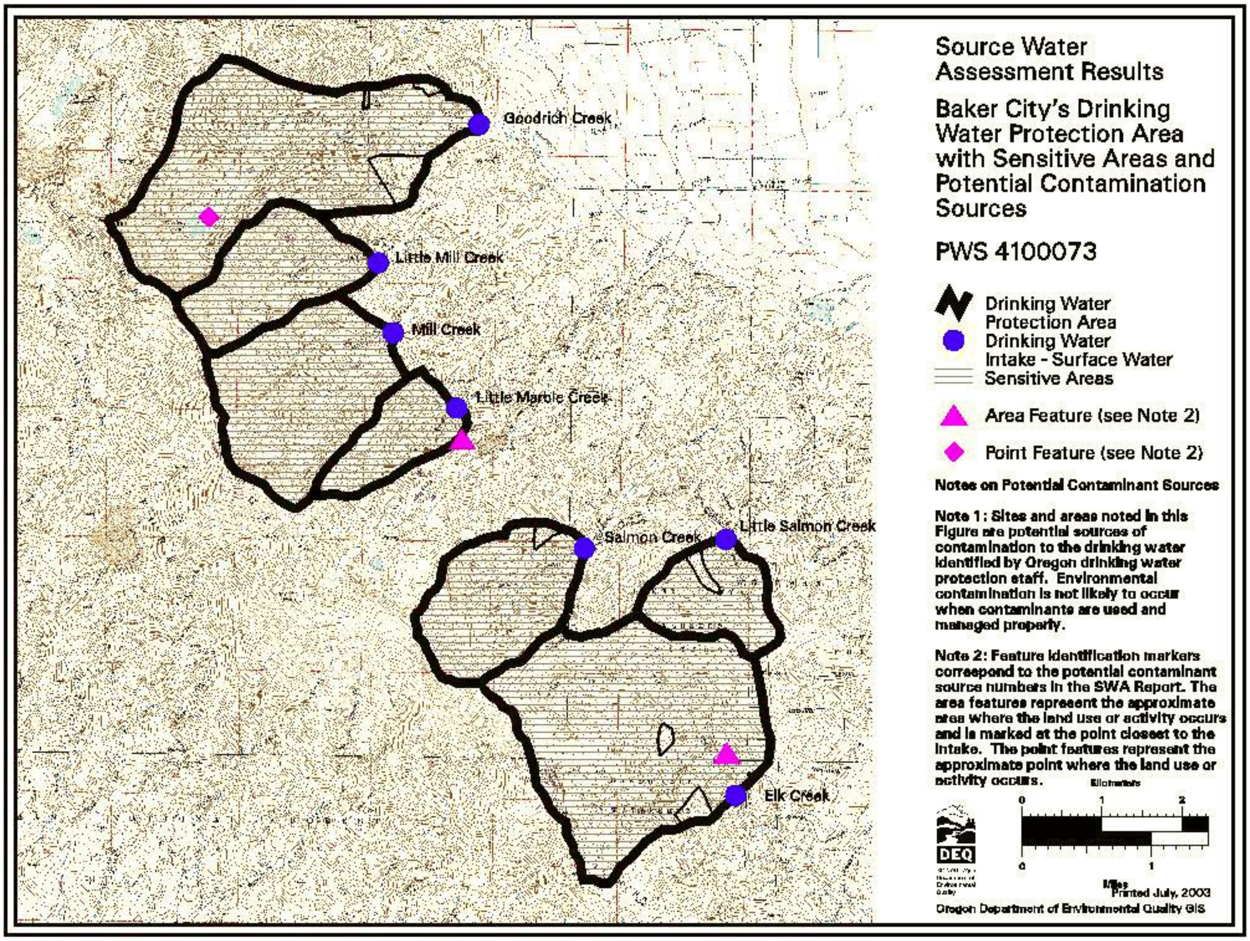

Figure 3. Map found in DEQ assessment report of Baker Cities drinking water source (7 creeks in the Elkhorn Mountains) outlining the source water protection area, and marking potential contamination source sites.

Unlike Reedsport and Baker City, the City of Portland conducted its own Source Water Assessment in place of the DEQ, following all the same procedures. In Portland's Source Water Map (see Figure 4), the source water protection area is outlined, but no potential contamination sources are highlighted. Though not marked on the map, Portland's Source Water Assessment says that the entire watershed upstream of the intake is a sensitive area, because the entire watershed could be a source for animal related microbial contaminant (City of Portland Water Bureau, 2006). This was the only potential contamination source listed, as the Bull Run watershed is closed to the public, and no timber harvest or development is allowed within the watershed. One possible threat that the Source Water Assessment failed to mention was the possibility of forest fires; the same possibility that drove the City of Bend to choose a membrane filtration system over a UV treatment system. A forest fire could render the Bull Run water source completely unusable for longer than groundwater alone could supply the city. However, the chance of a forest fire occurring is expected to increase with climate change, due to drier summers and increases in the mountain pine beetle and western spruce budworm population which are invasive species that cause tree mortality (Dalton, 2017). Tree mortality in turn could alter the hydrologic budget, posing additional water supply and water quality threats to the Bull Run watershed.

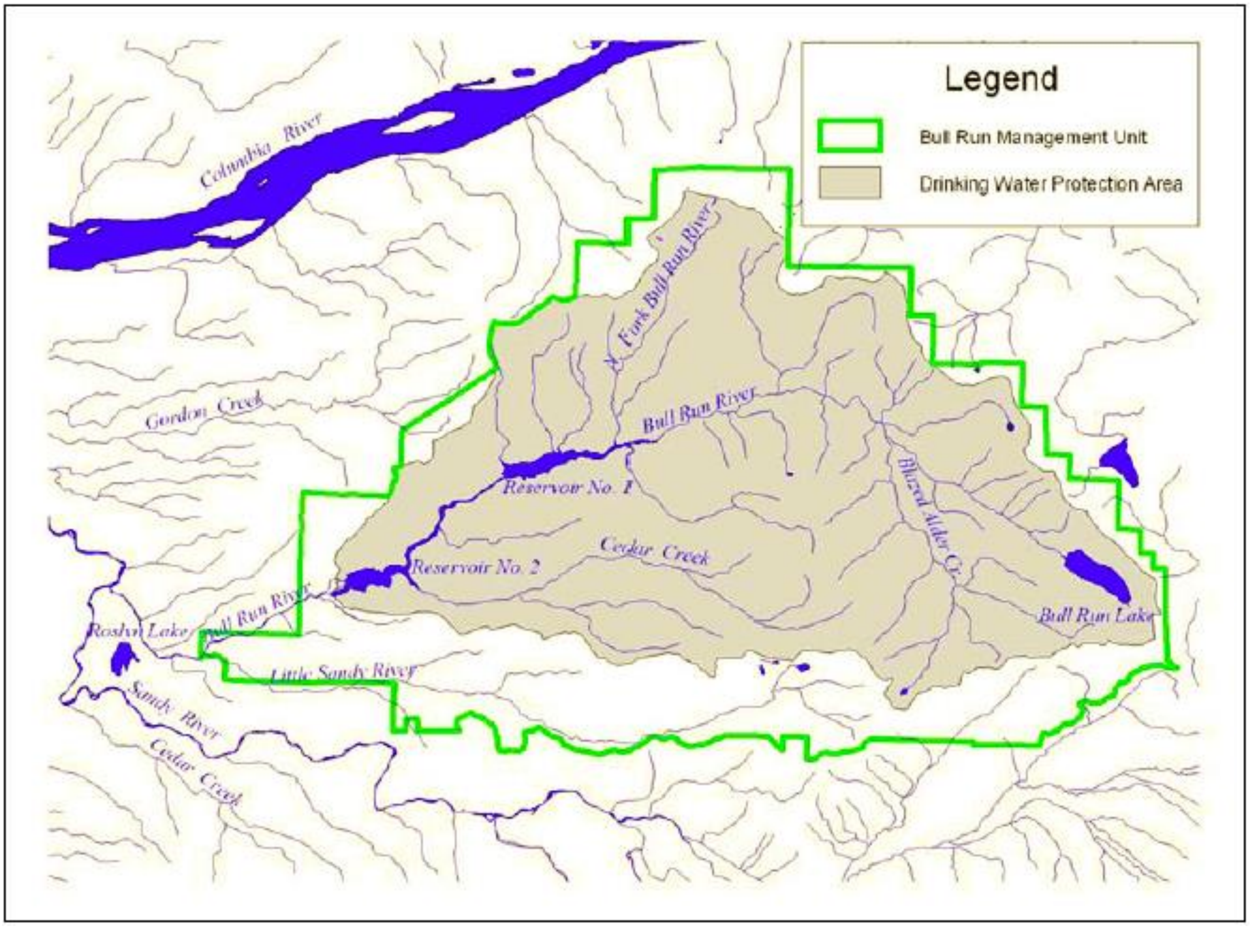

Figure 4. Map from the Portland Water Bureau's Source Water Assessment, outlining the source water protection area (no points of possible contamination were identified).

4.1 Water Quality Parameter- Weather Correlations

Using the DEQ Assessment reports, I attempted to graph correlations between the potential water quality threats that they mentioned, and the types of weather events that lead to an increase in certain water quality paraments. Figure 5 shows some examples of the graphs that were completed for this analysis. No correlations were found between turbidity levels in the water and daily precipitation totals for any of the three watersheds. The tests comparing precipitation to other contaminants such as chemical detections and disinfectant by products in the water supply also showed no correlations. Further analysis showed no correlations between temperature and bacteria or DBP's in the water supply. While the lack of correlations is unhelpful in modeling a clear relationship between water quality parameters and weather parameters, it does say something important about these three watersheds. The lack of correlations between precipitation and water quality parameters implies that the forested watersheds are serving their intended purpose and acting as a buffer around the water supply, infiltrating the precipitation and minimizing runoff. This implies that these water systems are effectively reducing the risk of contaminants getting in the water and in certain ways are resilience to weather fluctuations; however, when contaminants do get in the water, these systems don't have the ability to remove then and are still very vulnerable.

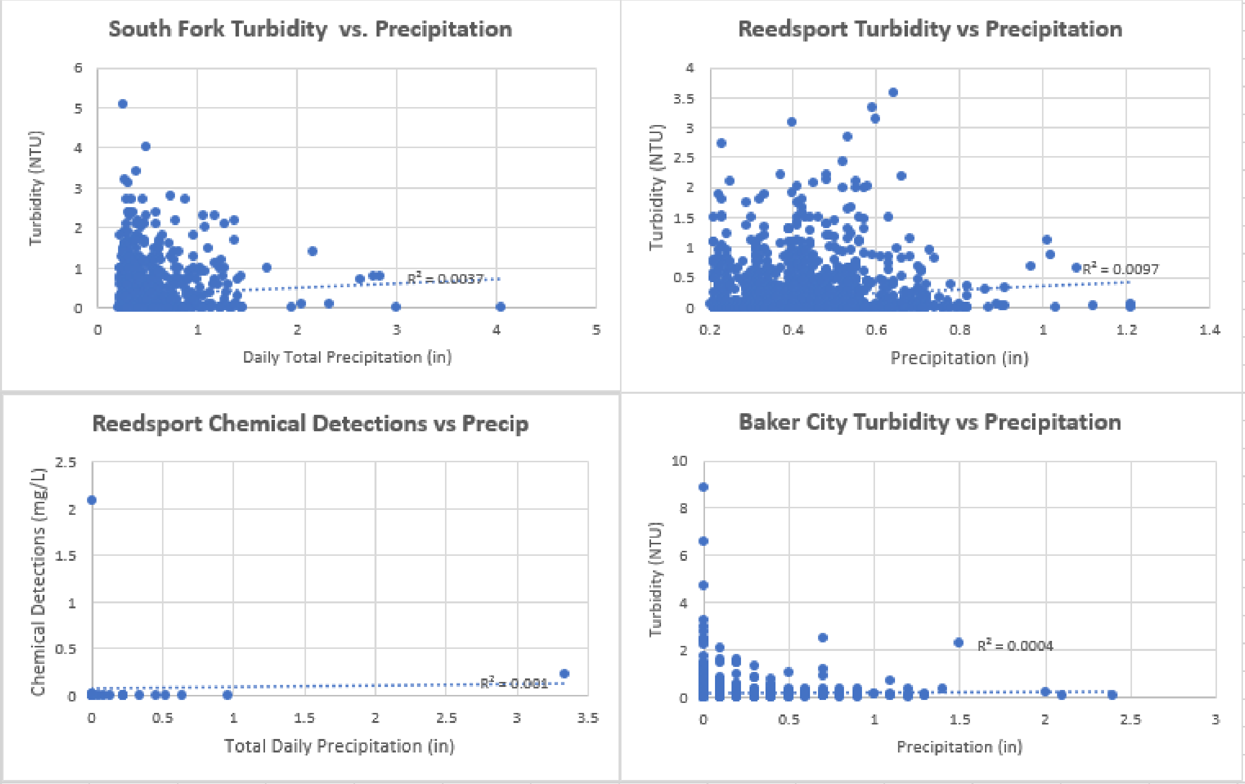

Figure 5. Examples of the graphs that were created for the potential water quality impacts in three watersheds – none of the graphs created showed any significant correlation or relationship.

4.3 2017 Cryptosporidium Findings: Hydrologic Analysis

This case study looks more closely at a particular water quality event in Portland's watershed and attempts to explain why it might have happened using a hydrologic analysis of one of Bull Run's tributaries (South Fork). This data therefore can't fully represent the whole watershed, but can serve as a learning tool. On January 2nd, 2017, a Bull Run sample tested positive for the pathogen cryptosporidium; samples for the following 2 months continued to detect trace amounts of the pathogen. The Portland Water Bureau is still unsure what caused the positive samples, but it was likely that animal scat was washed into the watershed during a storm event. There were several large storms in December, and then a relatively small one at the end of December, which was the last rainfall event before cryptosporidium was detected at the dam intake on June 2nd (Figure 6). Figure 7 shows a weak relationship between turbidity and discharge in one of Bull Run's tributaries (R^2 =0.37, $p < .05$); we would expect on average a discharge of 730 cubic feet per second (CFS) to create turbidity levels above 5 NTU – which would exceed EPA standards. The storm that preceded the cryptosporidium findings in the Bull Run watershed had a maximum discharge of only 243 CFS in the South Fork tributary.

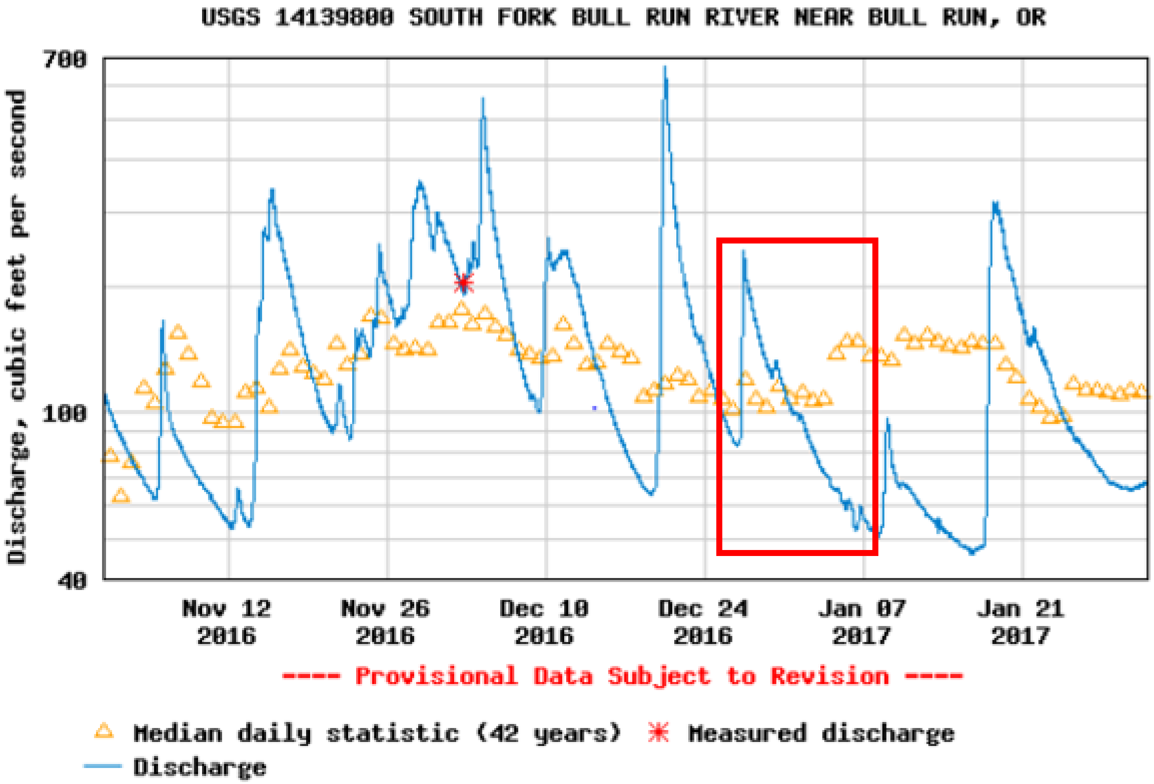

Figure 6. A hydrograph of the South Fork tributary, with the storm of interest highlighted in red.

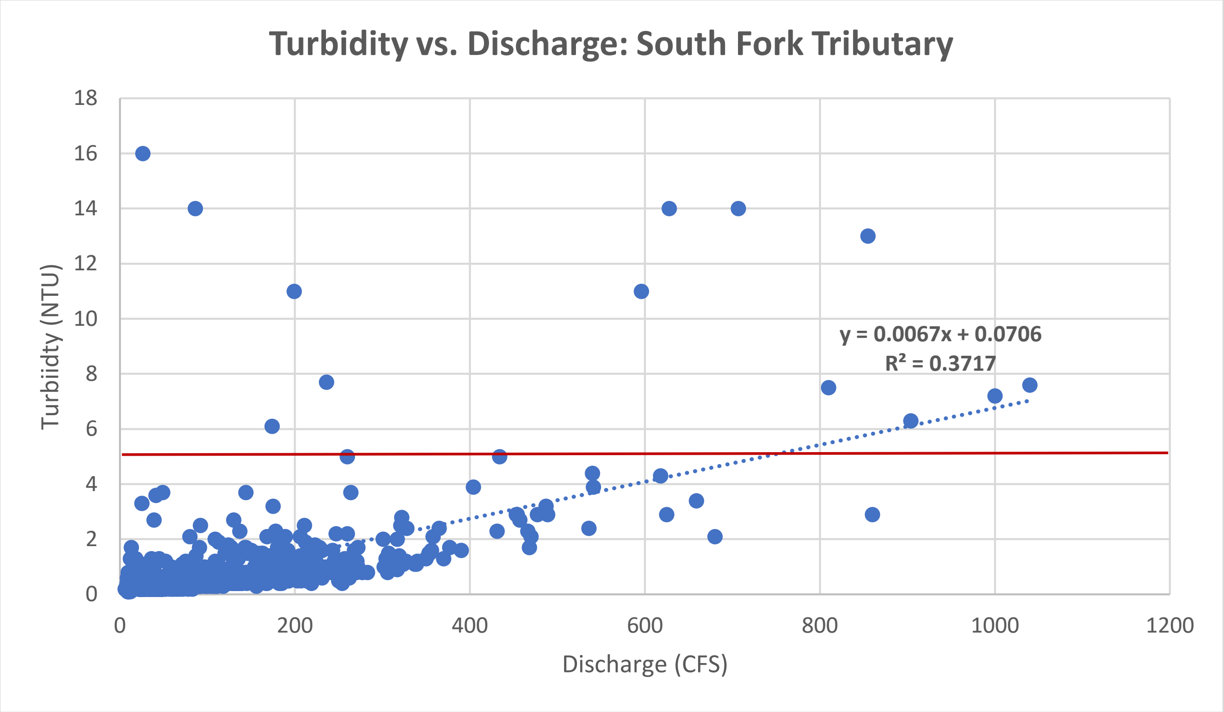

Figure 7. A graph showing the relationship between discharge and turbidity in Bull Run's South Fork tributary using daily averages from 1992-1994. The red line marks the MCL for turbidity (5 NTU).

The hydrograph seperation analysis (Figures 8 and 9) was used to calculate the average infiltration rate over the course of the December 27th^th^ -28^th^ storm. This technique assumes that the average infiltration rate over a time period is equal to the total precipitation during that time period, minus the total discharge: all of the water that has fallen that was not discharged through the stream is assumed to be infiltrated. This hydograph seperation analysis gave an infiltration rate of 0.03 in/hour throughout the course of the storm, which is a relatively low infiltration rate for a forested watershed. Furthermore, the runoff rate in relationship to the precipitation rate shows that 12% of the precipitation that fell during the storm was runoff. In comparison, the same calculation performed on a late summer storm in 2015, with double the amount of total rainfall, shows only 1% of the precipitation resulting in runoff.

An antecedent moisture index can help to explain why the percent of runoff in December 2016 was so high. The antecedent moisture index is calculated using a 30-day exponential decay calculation, that uses rainfall data for each day, along with the field capacity of the soil and the soil depth. This calculation is highly sensitive to the decay rate constant; a decay rate constant of 9.5 was used to determine antecedent moisture in Figure 10, however, a decay rate of .9 showed antecedent moisture decreasing over the course of the month. This calculation says that at the beginning of the storm on Decembe 27th, 2016 the antecendent moisture in the soil was 8.8 in., (Figure 10) which is relatively high. This is most likely due to the large storms that proceded the december 27th storm in December which are visible as the in Figure 10 as the small increases (postitive slopes) of the moisture in soil. The high level of antecedent moisture in the South Fork sub basin, and the low infiltration rates and high runoff levels duing the storm on December 27th-28th could be one possible explination for the presence of cryptosporidium in the watershed.

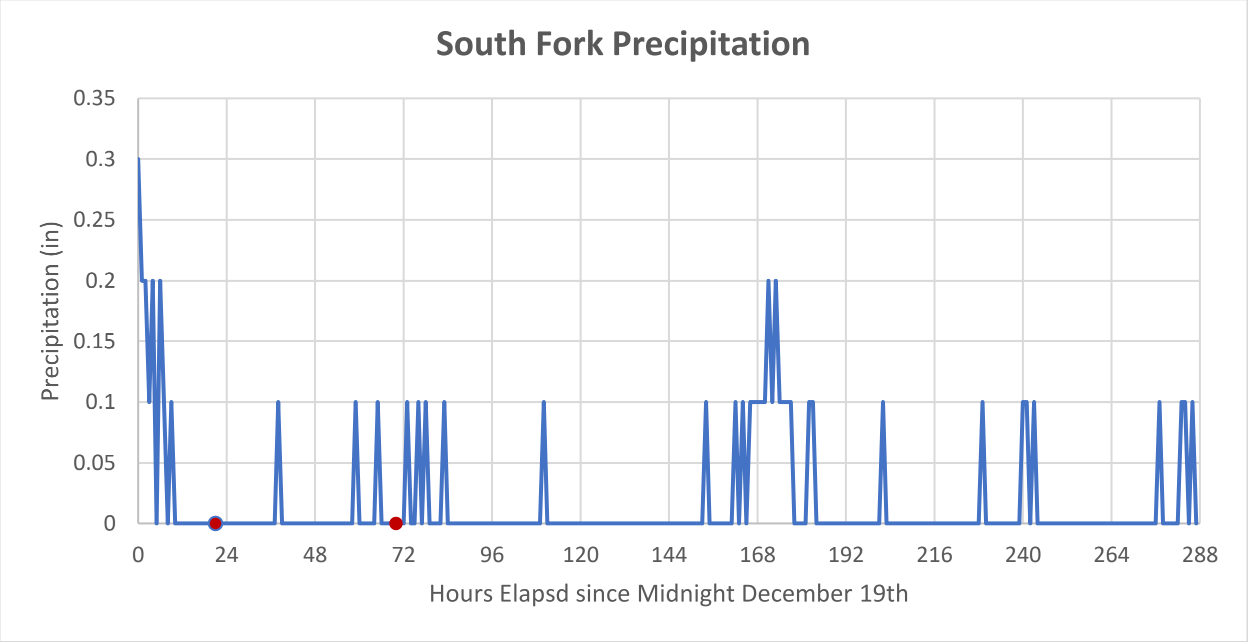

Figure 8. Hourly precipitation totals at the South Fork SNOTEL weather station leading up to and during the December 27th-28th storms preceding positive cryptosporidium samples in the source water.

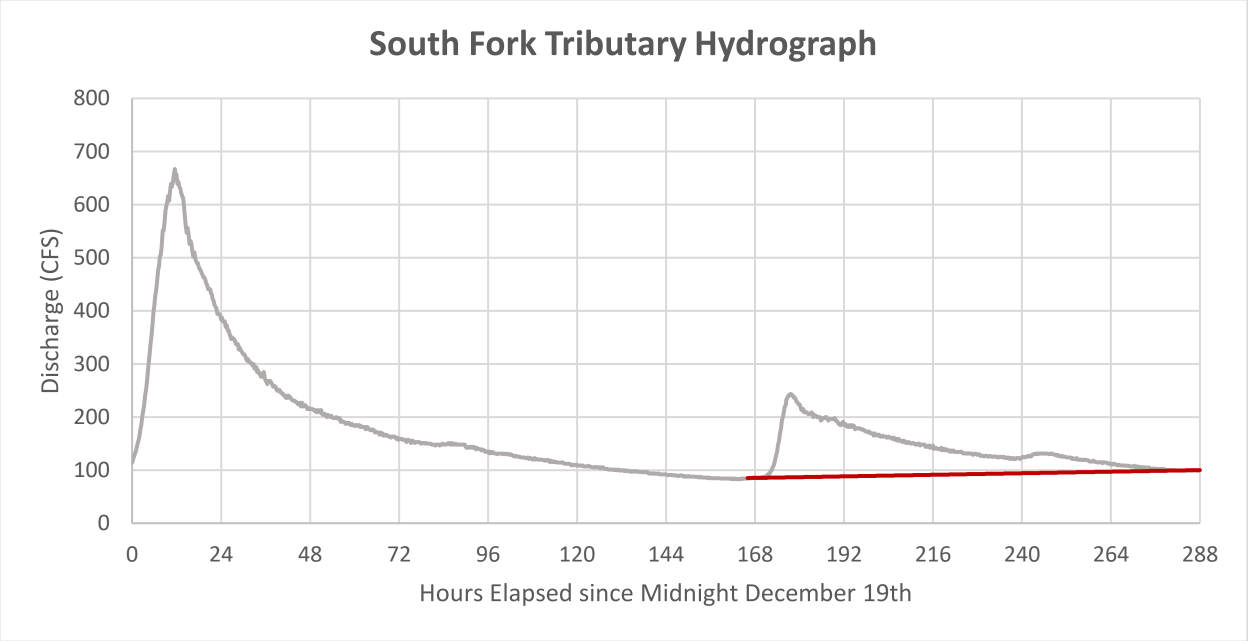

Figure 9. Discharge measured in the South Fork Tributary leading up to and during the December 27th-28th storm preceding cryptosporidium findings in the watershed.

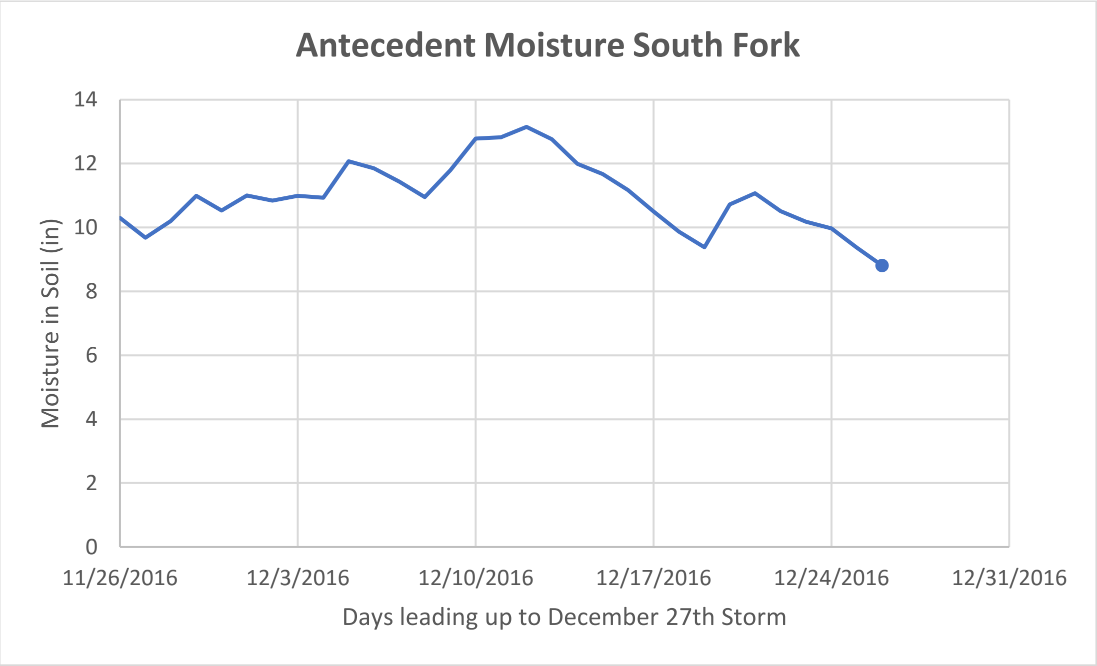

Figure 10. Soil Moisture levels in the South Fork sub-basin for the 30 days leading up to the December 27th-28th storm

What does this mean for the future? In December, the South Fork sub-basin received 17 inches total of precipitation. Figure 11 displays the relative frequency of this December rainfall totals at the South Fork weather station, showing that there is a 50% probablility of having a December rainfall total less than 17.4 inches. What this tells us is that precipitation in December 2016 in the South Fork Subbasin was nothing out of the ordinary; in fact the total precipitation level was less than the average (17.6 inches). Climate models predict that winter precipitation levels in the Pacific Northwest are expected to increase between 4.9% -7.9% by 2050 and from 7.3% to 14.5% by 2080 (Dalton et al.,2017). While December wasn't an especially wet month for the South Fork subbasin, on January 2nd, the date that the first water sample tested positive for cryptosporidium at the reservoir intake, the South Fork weather station was at 128% of its average annual precipitation (NRCS, 2017). So, while December conditions weren't necessarily wetter than average, the yearly precipitation was much higher than normal, which could explain high levels of antecedent moisture. While 128% of average precipitation is much higher than the new average we will expect to see with climate change (up to 14.5% by 2080), the wet conditions that we saw leading up to the cryptosporidium findings might no longer be unusual, but simply a typical "high" variation in rainfall.

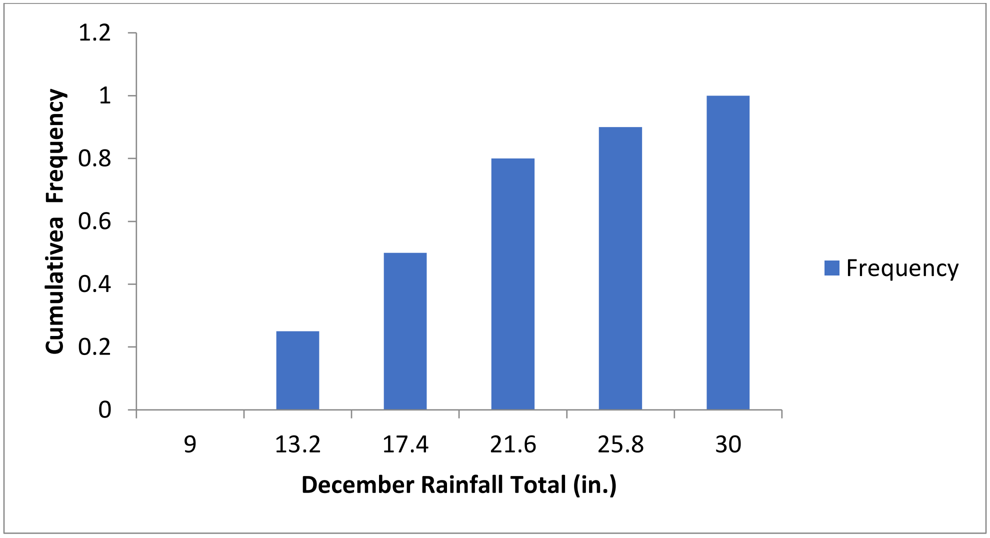

Figure 11. A histogram representing the cumulative frequency of precipitation totals for December, in the South Fork sub-basin, using data from 1997-2016.

4.3 Cost Analysis – Who Can Afford It?

In 2016, the city of Bend, which had previously had an unfiltered water supply, installed a 30 million-dollar filtration plant. They had been considering the implementation of a filtration system since 2012 and decided on the membrane water treatment filtration rather than cheaper options such as ultraviolet filtration, because this system had the ability to remove sediment from the water source in the case of forest fires (Borrud, 2013). The City of Bend was able to pay for the water filtration plant by increasing the water rate 5% for their 35,000 customers (Borrud, 2014). As shown in Table 2, a city like Portland, which serves 250,000 households directly (950,000 total) and has a median population income close to Bends, would most likely be able to afford the construction of a water filtration plant by raising water rates (US Census Bureau, 2017). In addition, the Portland Water Bureau would only need to raise rate by 6% to pay for the treatment plant in full over the course of two years. Table 2 also shows, that while Reedsport and Baker city have lower median household incomes than Portland and Bend, by a wide margin, the costs of installing a treatment plant would be much higher because of their relatively low populations. In fact, the rate increases are so high for Baker City and Reedsport (3-8 times higher than current rates) that it would be impossible for these cities to pay for a filtration plant in or less 5 years, without federal government assistance.

Table 2. The demographics of each city, and the costs associated with paying for the installation of a 30-million-dollar water filtration plant, over a 5-year time period.

Water Provider	Number of households	Household Median Income	Current Monthly Water Rate ($)	Percent Increase needed to pay for Filtration Plant	$ Added to Monthly Bill
Baker City	4329	$36,778	$50.51	255	$128.98
Bend	33396	$52,989	$35.90	5	$1.69
Portland	254167	$55,003	$33.83	6	$2.20
Reedsport	1833	$31,935	$22.35	658	$147.03

5. Discussion

5.1 The Turbidity Precipitation Relationship

Although relatively little has been written on the impacts of climate change on water quality for drinking water systems, certain studies have concluded that climate change will, in many places, lead to degradation of surface water quality (Delpla et al., 2009, Whitehead et al., 2009). This thesis attempted to analyze how big these impacts would be in Oregon's unfiltered water systems by looking at correlations between water quality and weather parameters. There are many possible explanations for why a linear relationship wasn't present - it could be because the data wasn't detailed enough (daily values) to notice a relationship, or because previous studies conducted were not focused on protected, forested watersheds used for drinking water. As noted earlier, the correlations between turbidity and precipitation are not clear, most likely because of the complicated runoff processes that take place in forested watersheds. Göransson et al. (2013) for example, found no linear correlations between turbidity, precipitation and discharge, but did find positive correlations during periods with high flow combined with heavy rainfall. Another study which collected various samples during and after high intensity rainfall and runoff events in small streams in Germany, found that there is a significant increase in turbidity/microbial contaminants during these types of events (Kistemann et al. 2002). This paper notes that the EPA does not currently require sampling during extreme weather events, even though, as their study showed, water quality during “normal” or dry conditions is not at all representative of water quality during heavy rainfall and runoff events (Kistemann et al. 2002). It’s important to note that this study correlated turbidity and microbial contaminants with extreme runoff events, measured through discharge in the reservoir’s main tributaries (Kistemann et al. 2002). If water systems managers are not already doing so, sampling at tributaries during extreme precipitation events would be an excellent way to better understand the impacts that runoff has on water quality during extreme weather events in each individual watershed. While studies have shown that the relationship between turbidity (or sediment load) and precipitation may not be a linear one, research has also shown that there is a -complicated- positive relationship between heavy precipitation and turbidity levels.

The most likely reason that there was not a correlation between turbidity and precipitation in this paper’s analysis watersheds is because the watersheds forests act as a buffer to the water supplies, by dampening the impacts of extreme weather. There are several ways that these forests protect water sources from contamination; first, in the summer the trees shade the entire watershed (and parts of the water supply) keeping the water flowing through the tributaries cool, and ensuring that the water retained in the soil does not all evaporate off. Second, the tree’s roots create more complex soil structure which creates higher infiltration capacity and porosity, decreasing overland flow. The forests allow much of the water that falls as precipitation to be infiltrated, until the soil becomes saturated and runoff begins; at this point washing contaminants, such as sediment, pathogens, and excess nitrates in the water. Because of these processes, we do not see a direct correlation between weather events and water quality parameters for these water systems like we might see in a less permeable watershed, and more complex hydrological analyses are needed.

The Bull Run cryptosporidium case study is an example of what could happen when the soil in a watershed becomes saturated due to large amounts of rainfall. The storm preceding the cryptosporidium findings in Bull Run, though small, had a relatively high amount of runoff (12%) compared to what we would see during drier parts of the year (1%). What we can tell from looking at the Bull Run cryptosporidium case study, is that wetter winters with the possibility of higher intensity storms intense rainfall events will increase the probability of pathogens (like cryptosporidium) getting in the water (Curriero et al., 2001). While the storm directly preceding the cryptosporidium detection was relatively small, the soil was already retaining a lot of moisture from several large storms that had taken place earlier that month, leading to low infiltration rates, and a relatively large amount of runoff. By January 2017, South Fork had already received 128% of its average annual precipitation, and while climate models only predict a 7- 14% increase in average rainfall by 2080, we can expect to see saturated soil conditions more frequently. While my analysis only focused on a small sub section of the Bull Run watershed (South Fork), and can't prove that runoff was the cause for the cryptosporidium findings, it is going to become increasingly important for each of these unfiltered water systems to complete a similar hydrologic analysis for their entire watersheds to better understand the runoff processes that occur.

One of the most helpful things that water system managers could do to better understand runoff processes would be to do watershed surveys and calculate soil permeability in various parts of the watershed, so that they can predict which areas in the watershed are more likely to become saturated and lead to runoff during storms. Once this is complete, water system managers could sample these "higher risk" locations during extreme precipitation/runoff events, to see how much turbidity levels change during these events. Because turbidity is used for a proxy for the probability of microbial contaminants getting into the water supply, water systems could then calculate what size of a storm would be necessary to cause runoff conditions that could pose a risk to the water supply, and what the probability of a storm of that size occurring in the future would be.

5.2 Other Implications for Water Systems

In the coming years, all unfiltered water system managers are going to need to make decisions about how to make water systems more resilient. It is important then, that evaluations of water systems susceptibility to climate change are done now, to prevent water quality issues in the near future. The climate in Oregon is already changing and cities such as Bend, OR have found that the costs of filtration are worth the benefits that it provides. Small water systems like Reedsport and Baker City, which both have - or have plans to install - a UV treatment plant have taken the necessary steps towards protecting their customers from microbial contaminants. These smaller cities, which would have a very difficult time paying for a membrane filtration plant, may be better served by investing in resilience through land management. Examples would include working with other land managers within the watershed to stop logging, and decreasing the amount of runoff into the water supply, which could still cause turbidity events. Managers of larger municipal drinking water systems that can expect an increased risk of contamination with climate change will most likely need to begin planning to put a filtration system in sometime in the future. In most cases, filtration is going to be necessary to maximize resilience to climate change and truly minimize the risk of contamination. In the case of drinking water however, there are two types of resilience. Filtration eliminates the risk of consumers drinking the contaminants that get into the water, while land management in watersheds minimizes risk of pollutants getting into the water in the first place. In drinking water systems, the best way to ensure resilience is through a combination of joint management of our water-energy-food systems and technological resilience.

In other types of water systems, in the United States and across the world, technology will sometimes play a part in increasing resilience, but it can’t get there alone. Management of water, energy and food systems need to change as well, to maximize resilience. In drought stricken regions, desalinization plants have been considered as an -expensive- method for creating a new water supply. However, desalinization plants can only go so far; they create a viable solution for wealthy communities in arid regions, but poorer communities will need to rely on decreasing their demand rather than creating new water supplies. For example, a change in water law in the western United States, which currently encourages stakeholders to use as much as they can to keep their water rights, is a policy that could drastically decrease usage for agriculture if changed. In rapidly developing cities such as Ho Chi Minh City, Vietnam, only part of the city's wastewater is treated before being dumped back into the river that serves as the drinking water supply. While new wastewater treatment plants will certainly help, water managers may need to seek alternatives for drinking water that can sustain a city that currently relies on bottled water for drinking. In rural farming communities, communication between water managers and farmers may be helpful in establishing fertilizer use strategies that minimize runoff and excessive nutrient pollution. In all of these cases, it is likely that similarly to my case study in Oregon, larger systems with more wealth will be able to afford increasing technological resilience to climate change, while smaller and poorer communities will need to rely on management strategies. The most important thing to keep in mind, is that both the new technologies and the new management plans need to be created with the ability to change and adapt to many different situations, as it is likely they will face unexpected situations that arise from climate change in the coming years.

5.3 Adaptive Management and Technological Resilience

The fact that smaller and often poorer communities (not just in the United States but globally) may not be able to afford technological resilience solutions raises important equity considerations. Communities that are not able to afford technological solutions will be impacted negatively. The water crisis in Flint, Michigan in 2015 highlights this issue; water system managers switched to an alternate water source because of monetary constraints and didn't take into consideration the consequences of a change to a more corrosive water source (Bellinger, 2016). The initial change to a new water source, and the decision to not treat the newly corrosive water were both cost saving measures; as Bellinger (2016) points out in his article on public health “the burden of childhood lead poisoning has always weighed most heavily on populations that are politically and economically disenfranchised”. Although the lack of technological resilience for poorer communities poses a threat, it also could create space for these communities to become more involved in alternative resilience policies. Land management policy, for example, as a method of increasing resilience of W-E-F systems would involve joint-cooperation of multiple stakeholders and landowners in a community.

Alternatively, adaptive management might be more effective than technological solutions in the long run. Adaptive management, especially in small or poor communities, could provide a more economical solution to environmental issues than investments in technology or infrastructure that may become obsolete in the future. It is also true that technological solutions are not always as stable as we might think; they depend on successful human design, and when poorly designed technology can create disasters. Take for example the failure of levees during Hurricane Katrina which resulted disastrously in the flooding of New Orleans; engineers commented afterwards in a congressional hearing that the failure of the levees may have been because they weren’t built to withstand a category 4 hurricane, but it also could have been caused by poor design (Kintisch, 2005). In a way, adaptive management is more of a resilient solution because of its ability to change. Granted, adaptive management policy needs to be created with the ability to change somewhat easily when it needs to. In his book *Who Rules the Earth*, Paul Steinberg explores the delicate balance between environmental policy that can’t be undone easily when political parties shift, but that can be changed without too much difficulty when situations arise that call for a change or improvement (Steinberg, 2015). This applies to management of water systems - if new research shows that the we aren’t managing our W-E-F systems effectively, we need to be able to change policy to reflect new findings - but it also applies to environmental policy in general.

Infrastructure (or technological resilience) has proved to be less flexible that adaptive management when it comes to new research. For example, it was only after extensive dam networks had been completed across the western U.S. that researchers began to see the negative consequences of dams for salmon (Limburg and Waldman, 2009) We've attempted to modify dams to address these issues by adding fish ladders, but the amount we can modify dams to better reflect our understanding of diadromous fish life cycles is severely limited, as we can see by the current movements focused on dam removal (Cosier, 2012). While it may be difficult to immediately pursue more flexible environmental policies on a global or even national scale, small communities may be the pivotal in creating resilience through adaptive management.

6. Conclusion

This study examined the water quality risks associated with unfiltered drinking water systems in Oregon in relationship to climate change, and attempted to identify approaches that water system managers could use to make these systems more resilient. While no direct correlation was found between weather parameters and water quality parameters, other studies have shown that there is a relationship between heavy runoff events and turbidity levels in water reservoirs. The precipitation regime preceding cryptosporidium findings in Portland's source water could be an example of one such event. While installing a filtration plant is a financially feasible and recommended option for water systems like Portland's, smaller water system's may not be able to afford technological resilience. This is possibly a pattern that we will see globally as communities begin to build resilience against climate change; poorer and smaller communities will often need to resort to joint land management, or adaptive management to increase resilience.

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