Impact of Four Oregon Fires on Drinking Water Systems: Risk Factors and Recommendations

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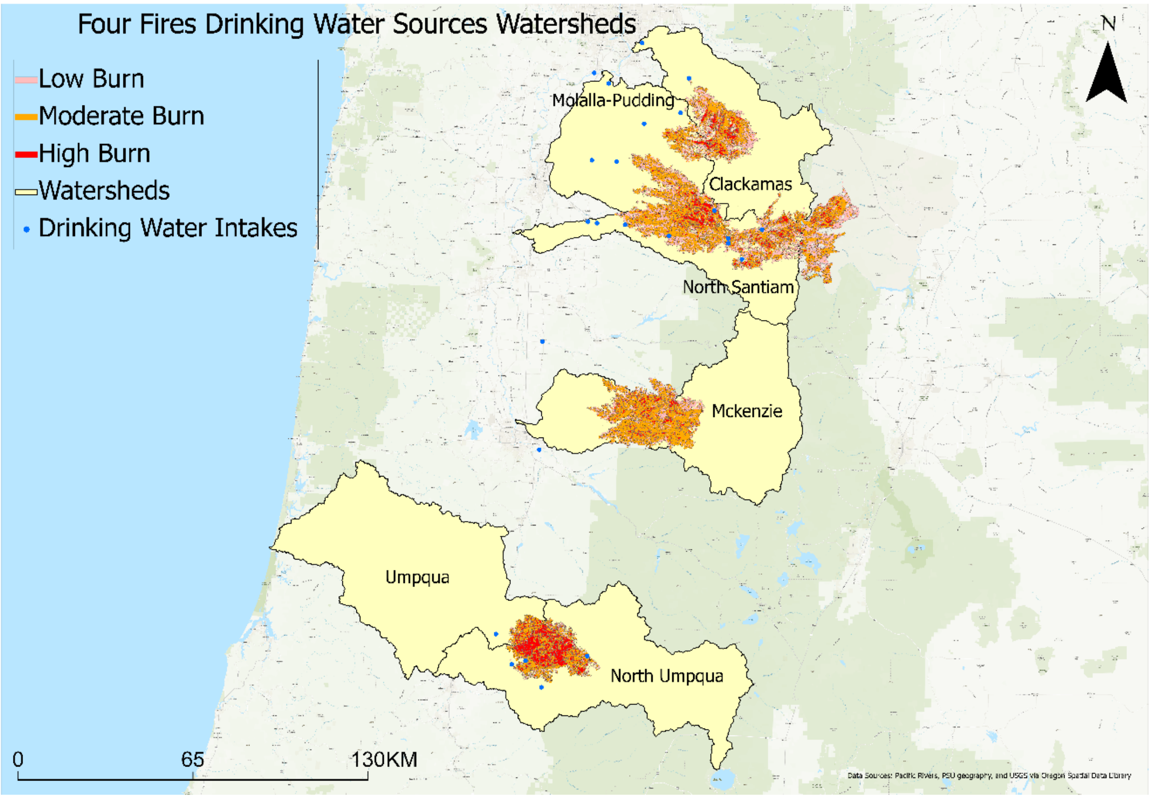
Introduction

The September 2020 fires in Oregon killed 11 people and damaged more than 4000 structures. They also affected more than a quarter million people in evacuation zones, with some without power for days. The sociopsychological and health impacts of fires are particularly challenging since they occurred during the COVID-19 pandemic. As wildfires become more frequent in the western United States as climate change-induced warmer and drier summers are projected, Oregonians need to learn lessons from the September 2020 fires and prepare for better futures. This report summarizes the characteristics and impacts of four major fires - Riverside, Beachie Creek, Holiday Farm, and Archie Creek Fires – and makes recommendations for reducing the risk of wildfires, focusing on drinking water systems. This report is composed of two main parts. The first part summarizes the four Oregon fires that occurred in September 2020 and their impacts on drinking water supply. In the 2nd part, the report presents technical background of the impacts to water quantity and quality in areas impacted by forest fires, drawing literature in the field. Additionally, this section reports how those changes affect municipal water supply systems and drinking water quality. Recommendations for opportunities to mitigate the risks associated with wildfire impacts to drinking water, including land management, are provided at the end. GIS analyses conducted for the fire areas provide the relative intensity of burn in the various watersheds and the populations impacted by these four fires; those data summaries are provided in Appendices A and B. Appendix C describes the source of the data and methods used in this report. We appreciate Rick George and Liz Gilliam for their comment on the initial draft. Views expressed are our own and do not necessarily reflect those of the sponsoring agency.

Part 1: Summary of four Oregon 2020 fires and their impact on drinking water supply

This section provides background information related to four fires that occurred in Oregon in the summer/fall of 2020 and a summary of the impacts to drinking water supplies as a result of the fires in the burned watersheds. Figure 1.1 shows the location of the four fires and watersheds affected by the fires.



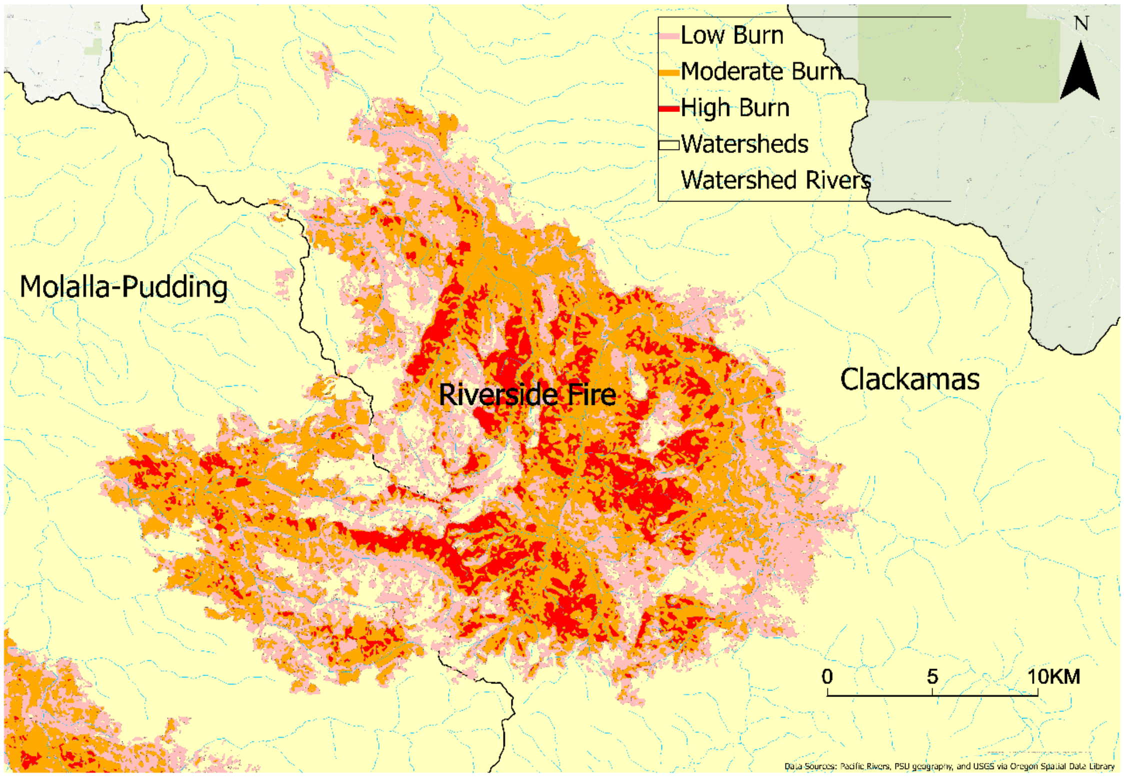
Data Sources: Pacific Rivers, PSU geography, and USGS via Oregon Spatial Data Library

Figure 1.1 The four 2020 Oregon fires that affected watershed drinking water supply system

1.1 Riverside Fire

The Riverside fire located in Clackamas County started on September 8th, 2020, and contained on October 8th, 2020, burned a total of 138,151 acres (Figure 1.2). The fire cost an estimated $21,000,000 in fire suppression efforts and destroyed 57 homes. The fire was centered in the rural and central area of the county including in the Mt. Hood National Forest and burned along a long stretch of the Clackamas River reaching the towns of Estacada and Colton. Between the Riverside fire and Beachie Creek fire to the south, in Clackamas County a total of 52,371 people were under level three evacuations (FEMA 2020a, Oregon Office of Emergency Management, 2020a).

The Riverside fire burned in 24 different subwatersheds, and there were 976 miles of streams within the fire zone. The effects on water quality were strong as the FEMA ETART reported a high risk to soil productivity due to increased erosion. Increases in erosion lead to more particulate runoff and greater threats to water quality. Expected recovery timing in more vulnerable areas is estimated between 2 and 5 years. It is estimated that soil erosion rates in post wildfire burned areas can triple even if the area is undisturbed after the fire. The impact on drinking water quality is that high levels of erosion lead to high increases in runoff of sediment attached pollutants and impact the quality of fresh drinking water (FEMA 2020a).



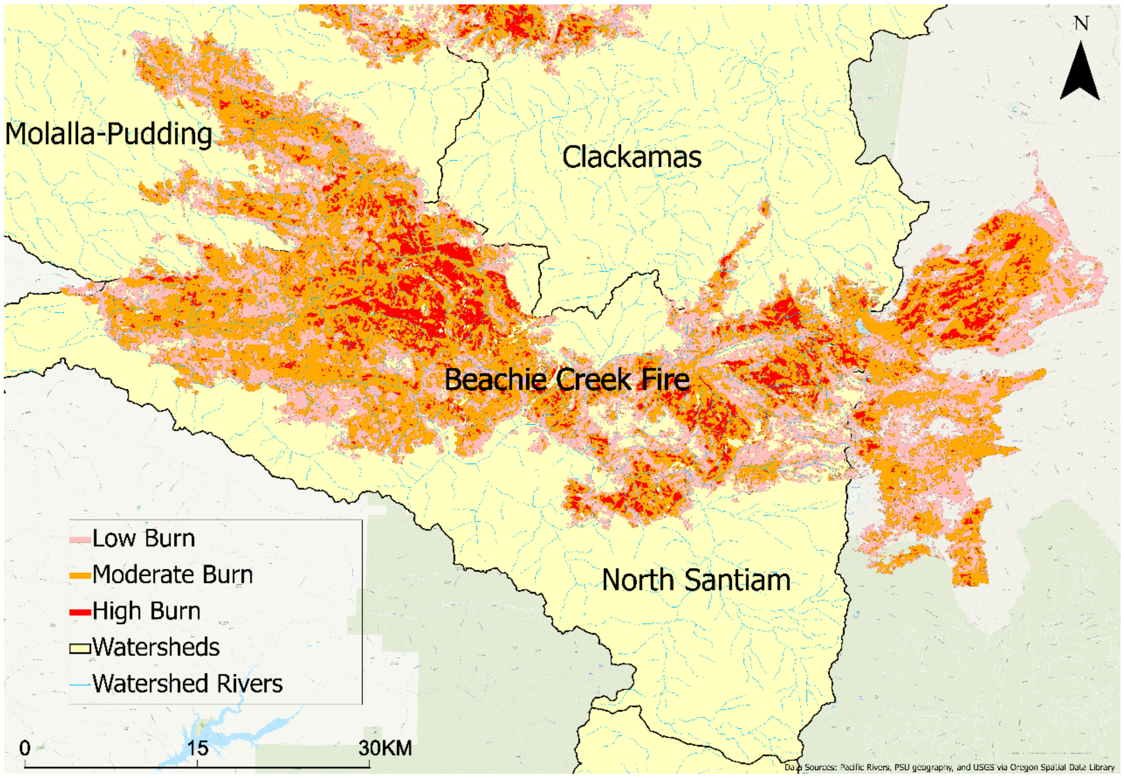
Data Sources: Pacific Rivers, PSU geography, and USGS via Oregon Spatial Data Library

Figure 1.2: Spatial extent and severity of Riverside fire and surrounding watersheds.

1.2 Beachie Creek Fire

The Beachie Creek fire, located in Linn, Clackamas, and Marion counties, started on August 16th, 2020, and was contained on October 31st, 2020. A total of 193,566 acres were burned (Figure 1.3). The fire cost an estimated $30,000,000 in fire suppression efforts and destroyed 470 homes. The fire was heavily positioned in southeast Marion County, south Clackamas County, northern Linn County, and in the Willamette National Forest. The towns of Lyons, Mill City, and Gates were among those heavily damaged. In Marion County, 720 structures were destroyed (FEMA 2020b; Oregon Office of Emergency Management 2020a).

The Beachie Creek fire burned in 12 different subwatersheds, and there were a total of 1,680 miles of streams within the fire zone. The effects on water quality were strongly noticeable as the soil productivity in the FEMA ETART report is listed as high risk of soil erosion. The report indicated that recovery of soil erosion is dependent upon vegetation recovery and that areas burned with low severity are expected to recover within two years; those more severely burned areas will require a longer recovery time (FEMA 2020b).



Data Sources: Pacific Rivers, PSU geography, and USGS via Oregon Spatial Data Library

Figure 1.3: Spatial extent and severity of Beachie Creek fire and surrounding watersheds.

1.3 Holiday Farm Fire

The Holiday Farm fire, located in Lane and Linn counties, started on September 7th, 2020, and was contained on October 29th, 2020. A total of 173,393 acres were burned (Figure 1.4). The fire cost an estimated $42,000,000 in fire suppression efforts. In Lane County alone, the fire destroyed 911 structures. The fire was centered in the western sides of rural Lane and Linn counties through the Willamette National Forest and followed the path of the Mackenzie River, heavily affecting the Mackenzie River watershed area and resources. The towns of Blue River, Vida, Nimrod, and Leaburg in Lane County were heavily affected and damaged by the fire, and 2500 people in these communities were displaced and 75% Blue River was destroyed. A total of 246,000 consumers in the county had reports of lost power due to the fire (FEMA 2020c; Oregon Office of Emergency Management 2020a).

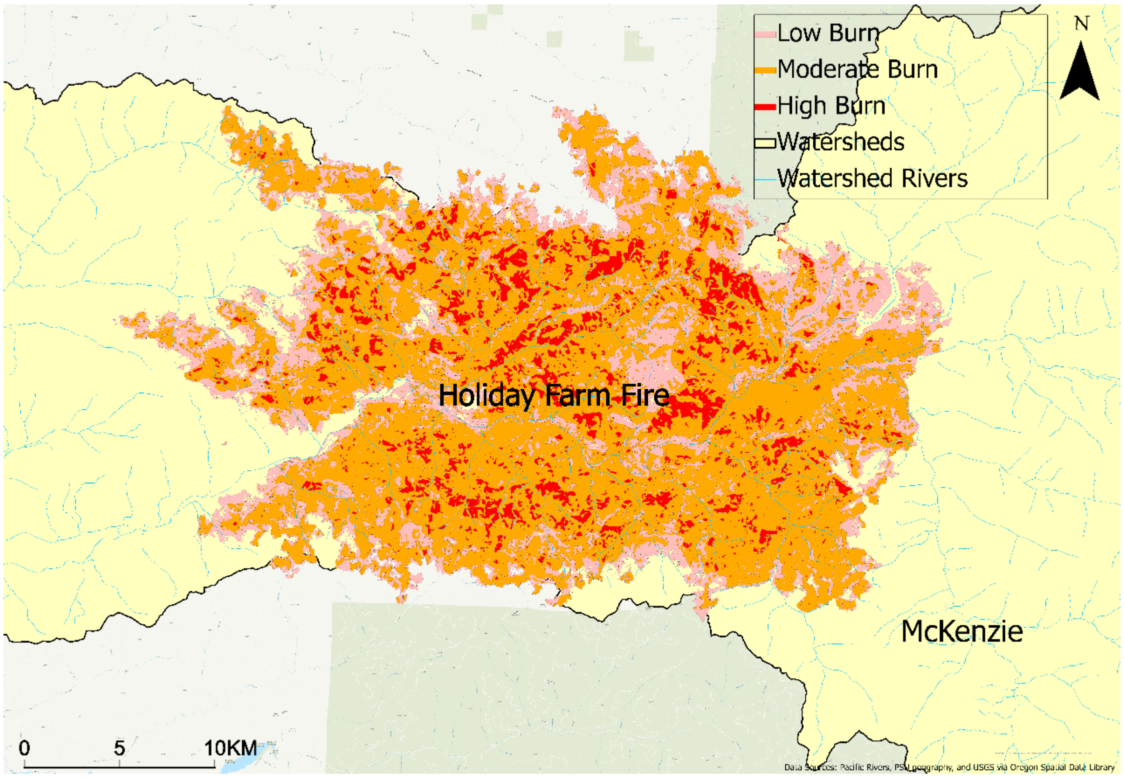


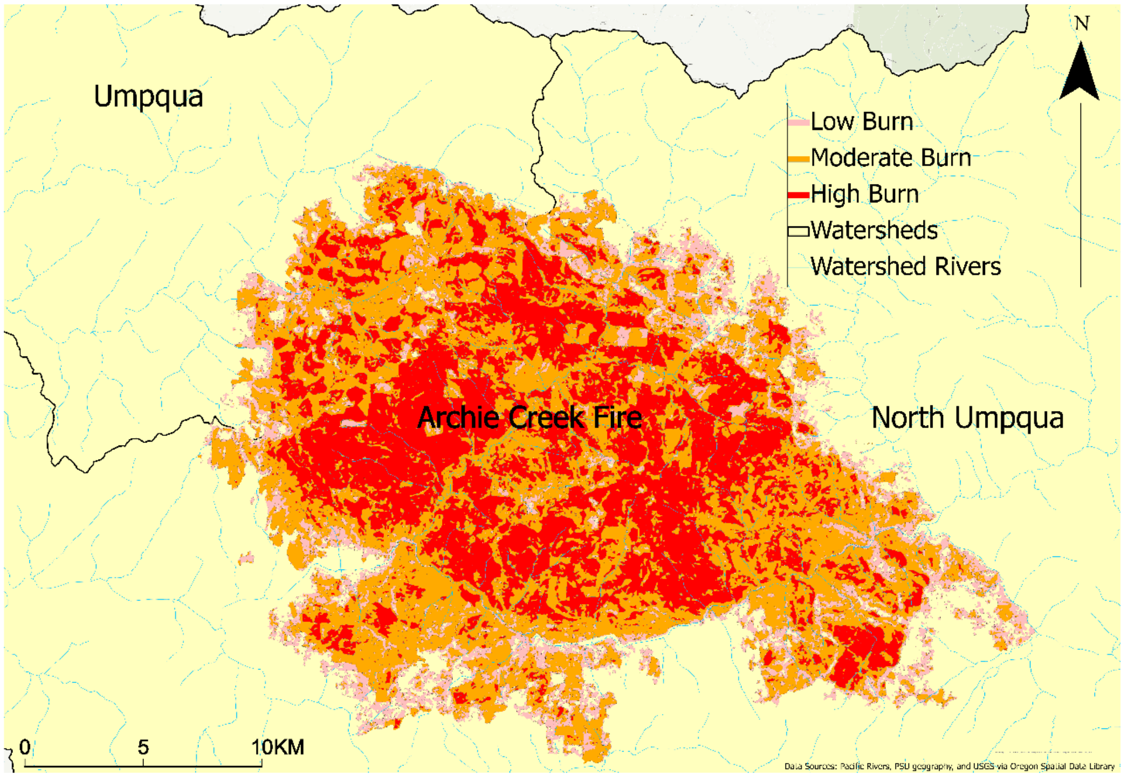
Figure 1.4: Spatial extent and severity of Holiday Farm fire and surrounding watersheds.

The Holiday Farm fire burned in 18 different subwatersheds, and there were 1,279 miles of streams that had some level of burning. Effects of the fire on water quality were felt strongly as multiple watersheds were left with a very high risk to soil productivity as assessed by the FEMA

ETART report. Large amounts and increased rates of soil erosion can compromise water quality. The estimated recovery for soil productivity is between 3-5 years for areas that were moderately burned as vegetation can regrow (FEMA 2020c).

1.4 Archie Creek Fire

The Archie Creek Fire located in Douglas County started on September 8th, 2020, and was contained on November 16th, 2020. A total of 131,596 acres were burned (Figure 1.5). The fire cost an estimated $40,000,000 in fire suppression efforts and destroyed 109 homes. The fire was positioned in the Umpqua River watershed near the communities of Glide and Steamboat, in northeast Douglas County in the Umpqua National Forest. The fire impacted a total of 100,000 people due to evacuations, damage, and smoke, and forced everyone living in Glide to evacuate. (FEMA 2020d; Oregon Office of Emergency Management 2020a).



Data Sources: Pacific Rivers, PSU geography, and USGS via Oregon Spatial Data Library

Figure 1.5: Spatial extent and severity of Archie Creek fire and surrounding watersheds.

The Archie Creek fire burned in 17 different subwatersheds for a total of 214,481 acres in those watersheds, and there were 968 miles of streams within the fire zone. The effects on the water quality were significant as the FEMA ETART report documented a very high risk to soil productivity due to highly increased erosion, and areas of clear-cut ground cover could take longer than 2-5 years for vegetation to stablish and decrease erosion. The impact on drinking water quality is that high levels of erosion lead to high increases in water runoff of pollutants and poorer quality of fresh drinking water. The FEMA ETART report documented significant hydrologic damage to fish and wildlife as areas with stream that were burned suffered increases in water temperatures due to loss of canopy cover in riparian areas. Temperatures are not expected to stabilize until several years and even up to 10 years in severely burned areas. Recommendations to address these issues include reforestation and natural regeneration (FEMA 2020d).

1.5 Impact on drinking water supply

The Oregon Wildfire Spotlight article by Oregon Office of Emergency Management assessed overall damages of the 2020 Oregon wildfires and shared a damage report completed by the Joint Preliminary Damage Assessment that looked at the counties of Clackamas, Douglas, Jackson, Klamath, Lane, Lincoln, Linn, Marion. The report found estimated damage totals as a sum in these counties to have costs of $310,878,021 in debris removal, $1,398,564 in water control facilities, $24,724,250 in utilities, and a total of all categories adding up to an estimated cost of $380,228,948. The EPA was involved in the recovery process of the fires; one of their recovery focuses was on water quality. The EPA performed treatment on the streams of Bear Creek in Jackson County, Little North Fork Santiam River and North Fork Santiam River in Marion County and Linn County, Salmon River and Panther Creek in Lincoln County, McKenzie River in Lane County, and the North Umpqua River in Douglas County. Treatment focused on the use of using straw wattles as runoff levees for removing hazardous waste and mitigating soil erosion on 226 different properties along those streams. In addition, EPA drinking water engineers assisted in the relief and recovery process by testing drinking water systems sourcing water from affected streams. Following the 2020 Oregon wildfires, the state of Oregon legislature enacted policy to extend the 2020 Wildfire-Impacted Wells Testing program into 2023, and this policy allows for free water quality testing for individuals affected by the fire who use wells as a drinking water source. The method for estimating population numbers that are affected by the fires in each watershed is described in appendix 2 (Oregon Office of Emergency Management 2020a, 2020b).

References

FEMA (2020a) Riverside Fire: Erosion Threat Assessment/Reduction Team (ETART) Summary Report https://gscdn.govshare.site/1aa8ace4addf06592a8d7dcb775413bf10fd1ec6/ETARTSummary-RiversideFire.pdf

FEMA (2020b) Beachie Creek Fire: Erosion Threat Assessment/Reduction Team (ETART) Summary Report https://gscdn.govshare.site/1aa8ace4addf06592a8d7dcb775413bf10fd1ec6/ETARTSummary-BeachieCreekFire.pdf

FEMA (2020c) Holiday Farm Fire: Erosion Threat Assessment/Reduction Team (ETART) Summary Report https://gscdn.govshare.site/1aa8ace4addf06592a8d7dcb775413bf10fd1ec6/ETARTSummary-HolidayFarm.pdf

FEMA (2020d) Archie Creek Fire: Erosion Threat Assessment/Reduction Team (ETART) Summary Report https://gscdn.govshare.site/1aa8ace4addf06592a8d7dcb775413bf10fd1ec6/ETARTSummary-ArchieFire.pdf

Oregon Office of Emergency Management (2020a) 2020 Oregon Wildfire Spotlight, https://oregon-oem-geo.hub.arcgis.com/apps/2020-oregon-wildfire-spotlight/explore

Oregon Office of Emergency Management (2020b) Oregon Wildfire Response & Recovery https://wildfire.oregon.gov/

Part 2: Forest fire impacts on water quantity and quality and municipal water supply systems

2.1 Water quantity impacts

2.1 1 Water Supply

Most cities in the Willamette Valley rely on pristine upland forest watersheds to collect, filter, and deliver precipitation to rivers, reservoirs, and groundwater (Jager et al., 2017; Jung and Chang, 2011). Unprecedented wildfires in the summer of 2020, 17 in total, burned more than a million acres in Oregon, marking it to be the most destructive fire season on record (Seeds et al., 2020; Urness 2020). Intense and severe wildfire removes vegetation and organic matter, creating a hydrophobic layer on top of the soil profile (Certini 2005; Larsen et al., 2009; Woods et al., 2007). The loss of vegetation reduces the interception and evapotranspiration ability of the watershed (Blount et al., 2019; Wang et al., 2020), causing more precipitation to fall directly on the ground. The water repellent layer of ash on the soil surface encourages more runoff by reducing infiltration rates and reducing groundwater recharge in the process (Beatty and Smith, 2013; Shakesby and Doerr, 2006). During winter storm events following fires, hydrophobic soils change the timing and magnitude of peak flows (Leopardi and Scorzini, 2015; Niemeyer et al., 2020), causing higher stormflows and quicker discharge of water into streams, forming more frequent flash floods and debris flows (Kean et al., 2016; Moreno et al., 2020; Wall et al., 2020). Combustion of vegetation and charred trees creates black carbon, which, when deposited on snowpack, can decrease snow albedo and accelerate snowmelt in spring, lowering the summer water supply (Gleason et al., 2019; Yan et al., 2021). Additionally, the decline in groundwater recharge can cause summer low flows to decrease when water demand is high, causing a need for modification of intake points and reduction in municipal water supply (Bart and Tague, 2017; Ball et al., 2021).

2.1.2 Water Delivery System

Headwater systems are crucial in providing water supply to downstream communities, with important infrastructure such as reservoirs, pipelines, intake stations, and treatment facilities (Leonard et al., 2017). For public water systems, landslide and debris flows are two erosional risks that can threaten water infrastructure both in upland and downstream, especially in the urban-wildland interface (Nyman et al., 2015; Parise and Cannon, 2011). Wildfire burning close to urban areas and water intake pipes have the potential to damage infrastructure such as pipelines, pump stations, storage tanks, and treatment plants (Hubbs and Muephy, 2019). For example, the 2017 Tubbs Fire in Santa Rosa, the 2018 Camp Fire in Butte County, and the 2018 Klamathon Fire in Siskiyou County, all severely damaged municipal water distribution systems, leaving residents without water for weeks and causing significant economic damage ($8M, $23M, $1.7M, respectively) (ca.gov, 2021; Proctor et al., 2020). Damaged water delivery systems can leak toxic chemicals into water distribution pipes, increasing immediate health risks and rendering drinking water systems unsafe (Solomon et al., 2021; Whelton, 2021). Private storage tanks and wells are no exception (Johnk and Mays, 2021; Scarponi et al., 2020), especially in the state of Oregon, where about a quarter of the state's residents relies on private wells for drinking water (oregon.gov, 2022). Damaged and contaminated private wells force rural communities to seek alternate sources of water, further increasing water demand and challenges to water delivery in the region (Bolstad, 2022).

2.2 Water Quality Impacts

2.2.1 Surface erosion, sedimentation, and debris flow

Wildfire burned areas have increased in the past decade, and surface erosion and sedimentation are expected to increase as well (Shakesby, 2011), which can negatively impact western US communities that rely on rivers and reservoirs for drinking water supply (usgs.gov, 2017; Chen and Chang, in press). The removal of vegetation through combustion changes the soil properties and creates hydrophobic landscapes that promote increased erosion and runoff. Erosion can carry water pollutants, both physical and chemical, into streams, rivers, and reservoirs. The increases in sedimentation input in streams cause higher turbidity as fine particulate matter (Murphy et al., 2012; Smith et al., 2011), and carries nutrients, metals, and organic matter- that can all increase challenges for drinking water treatment. From a water provision and water quality regulatory perspective, turbidity and suspended sediment concentration are the main sources of fine particle pollution and act as agents of carrying potential contaminants such as viruses and bacteria (Chen and Chang 2014).

There are many pre and post-fire factors that influence the timing and magnitude of sedimentation and turbidity, based on recent changing climate, fire regime, and land use. Wildfire characteristics, such as fire extent and severity, are often indicators of the timing and magnitude of turbidity response, with numerous studies discovering strong positive correlations between them (Hohner et al., 2019; Rhoades et al., 2019). Wildfire impacts are typically proportional to fire extent; the larger the % burn area, the higher the turbidity level in subsequent years following the fire (Hohner et al., 2019). Moderate to high burn severity fires are more frequently found to have the strongest association with elevated turbidity levels (Caldwell et al., 2020; Rhoades et al., 2011). Landscape characteristics are often linked to controlling wildfire extent and severity while also influencing the post-fire vegetation recovery and sediment transport and mobilization. Characteristics such as hydrologic connectivity, geomorphology, and land use are important in controlling the amount and rate of post-fire sediment export and turbidity changes (Hohner et al., 2017; Robinne et al., 2021). A recent study on turbidity levels following a major fire in California suggests that dams and reservoirs promote the longitudinal plunging of fine sediment particles and may dampen post-fire turbidity response downstream (Wright and Marineau, 2019).

With the expansion of urban development into forested areas, especially in the Western US, wildfires have been given more opportunity to cause more damage. Compared to less disturbed watersheds, urban watersheds are likely to show higher turbidity and sediment yields due to fragmentation of land cover, impervious surfaces, and quick routing of surface runoff through pipes (Oliver et al., 2012). The degree of landscape fragmentation at a subwatershed level has been linked to changes in total suspended solids in a mixed land-use watershed (Chang et al., 2021). Following wildfires, intense precipitation can increase runoff, flooding, and debris flows. Post-fire debris flows can occur without warning following intense precipitation and may cause large woody debris to strip riparian vegetation, block water intake sites, and damage treatment structures (Cannon and Gartner, 2005). Turbidity and suspended sediment response following wildfires are strongly correlated with precipitation and peak discharge patterns (Burke et al., 2013; Sequeira et al., 2020; Son et al., 2015). Intense precipitation can remain a major driver for the mobilization of sediments and elevated turbidity levels, which follows a seasonal pattern and may remain elevated for more than three years following the fire (Thompson et al., 2019).

2.2.2 Nutrient and dissolved organic matter

Nutrients and organic matters are commonly attached to soil particles during erosion events (Hampton et al., 2022). Dissolved organic carbon (DOC), nitrogen, and phosophrous are common chemicals produced in a wildfire by burning organic matters (Uzun et al., 2020), burned watersheds can often exhibit 10 times higher DOC concentrations than unburned watersheds (Revchuk and Suffet, 2014). The influx of nutrients and changes in stream water chemistry can accelerate ecosystem metabolism and promote bacteria and algae growth (Betts and Jones, 2009). Elevated levels of DOC can alter the chemical properties of disinfection byproducts (trihalomethanes, haloacetonitriles, chloral hydrate, dichloroacetonitrile, and haloketones) during chlorine disinfection at water treatment plants (Writer et al., 2014), increase treatment difficulties and cost (Chow et al., 2019; Wang et al., 2015). Dependent on the proximity of fire to drinking water intake, the intake site might be exposed to higher concentration of post-fire chemical contaminants and may need to relocate, or the water may remain treatable but will require additional treatment methods to meet drinking standards (Hohner et al., 2016). Fires burning close to the Wildfire Urban Interface in highly urbanized watersheds may expose heavy metals and nutrients to drinking water intakes and contaminate stormwater in developed areas (Bracmort, 2011; Proctor et al., 2020). Prolonged periods of stressed drinking water systems not only create challenges to meet municipal drinking water needs but also the requirements for the Safe Drinking Water Act.

2.3 Drinking water delivery systems

2.3.1 Surface water distribution system pollution

In addition to direct contamination from burning of organic compounds in drinking water source, damages and pollutants are also prevalent in surface drinking water intake points (Sever 2020). Wildfires burning close to the urban-wildland interface and water distribution networks can volatilize materials that are usually present in developed areas, such as plastic pipes and metals (Whelton et al., 2019). When fires are burned in urban areas, toxic chemicals and residues can pollute drinking water and air quality, from combustion of infrastructure, electronics, plastics, car, and oils (Chow et al., 2021). Direct release of these toxic chemicals and heavy metals can pollute drinking water systems, and undetected damages can also release toxic chemicals over time. Microplastics can also be generated following fires, and high temperature wildfires have the potential to promote plastic fragmentation (Hu et al., 2021). Case studies of the California 2017 Tubbs fire and the 2018 Camp fire found that post-fire toxic chemical levels in water distribution networks have reached hazardous levels and exceeded EPA thresholds by 12 magnitudes, which can cause immediate health effects when consumed (Whelton et al., 2019). The primary chemical release from burning of plastic pipes is Benzene, a toxic petroleum compound known to cause cancer and neurological problems. Water treatment plants may need to shut down the delivery system for repair and replacement of pipelines, to ensure no after-burn chemical residues are leaching into drinking pipes and continue monitoring efforts to ensure water quality is up to EPA standards.

2.3.2 Groundwater distribution system pollution

For communities in Oregon that rely on groundwater well sources for drinking water, wildfire can also pose great risks. Similar to surface water intakes, groundwater wells can be subjected to intense heat and cause damages to covers, seals, and wires around the well. The loss of vegetation from burning can cause well heads to be completely exposed to debris and sediment generated post-fire (Seeds et al., 2020). On lands where wells are owned privately, wildfires damages may be difficult to assess, since there are storage tanks, pipes, and treatment equipment that could also be exposed to intense heat and cause toxic chemicals to leach into the well, tanks, or pipes (Isaacson et al., 2020). For groundwater springs that are connected to public drinking water systems, groundwater can be contaminated through aquifers, potentially increasing the concentration of several parameters such as sulfate, fluoride, phosphorus, and nitrogen (Johnk and Mays, 2021; Mansilha et al., 2020).

2.4 Post-fire management

2.4.1 Fire fighting and Salvage logging impacts

During the fire fighting process, fire retardants (e.g., PFAS) are common chemicals used to suppress fires, which can be highly toxic when leached into waterbodies and soil (Norris and Webb, 1989). Traditionally, flame retardants are made out of ammonia and nitrogen, both highly noxious and can adversely affect water quality, damage aquatic organisms, and promote bacteria and algal growth (Alpers 2020). The degree of impact is based on proximity of application to streams, if application area is carefully selected to avoid headwater systems and drinking water sources, fire retardants can be safely used in the watershed without impacting surface water quality (Crouch et al., 2006).

Post-fire timber harvest activities are common practices to salvage the economic value of trees and to reduce hazards of falling trees. There are various benefits to salvage harvesting, such as preventing insect attack, reducing fuel for reburns, and preserving high-quality woods for commercial use (Peterson et al., 2009). However, many recent studies reported more negative impacts on sediment export and turbidity levels in burned and salvaged logged watersheds, likely attributed to the creation of logging roads (which lead to soil compaction and thus increase runoff), which are the largest source of erosion following wildfires (Lewis et al., 2019). In burned watersheds, salvage logged areas exhibited higher turbidity levels and retained them for longer periods than unharvested areas, slowing down the recovery of sediment exports (Emelko et al., 2011; Smith et al., 2012). The current salvage logging activities are motivated by timber economic value preservation and crisis management without carefully considering the watershed’s hydrology and vegetation diversity (Augustynczik et al., 2020).

2.4.2 Management practices

The degree of impact to riparian areas directly relates to degrees of impact to drinking water quality (Webb and Falk, 2019), whether it is burn severity, or vegetation mortality, riparian zones are buffers to potential runoff-related pollutions (Dwire and Kauffman, 2003). If wildfires are burned in hillslope areas and riparian areas remain intact or less burned, riparian vegetation can act as filters to capture sediments and debris (usfs.gov, 2014) and act as bank erosion control. The increased woody debris and sediment along the riparian area can help slow stream velocities and provide important habitats for aquatic species. Vehicle traffic on burned roads should be reduced to a minimum, to reduce additional soil compaction and erosion, which can reduce infiltration and storm runoff, and too intensely managed lands could promote significant sediment erosion (Prats et al., 2020). Salvage logging and other post-fire logging activities, if not carefully selected over a burned watershed, can further increase sediment delivery to streams, further threatening drinking water supply and aquatic habitats (Chen and Chang, in press). Post-fire land use and management practices can influence the trajectory of regrowth, recovery, and restoration (Stevens-Rumann and Morgan, 2019). Tree planting of native tree species will aid the speed of natural regeneration, and can shift forest diversity from corporate timber species (Barkley 2019). Accelerated recovery of trees and understory shrubs can reduce drinking water quality impacts sooner, by restoring the ecosystem functions of forested watersheds (Vasques et al., 2022).

2.5 Damage and cost evaluation

2.5.1 Economic loss

Wildfires in the Western US, when burned close to the urban-wildland interface, can cost drinking water systems millions of dollars of damages (Table 1). When evaluating the economic loss to drinking water systems, several cost factors are associated with the supply, storage, treatment, and delivery systems. The loss of water storage usually occurs in water reservoirs, where pollution from wildfire is so severe that the direct and indirect impacts cause a portion of the stored water to be lost or undergo very expensive treatment, which can cause millions of dollars in value lost. Storage loss is commonly caused by elevated sediment concentration (turbidity), nutrients (nitrate, phosphorous), and dissolved organic carbon. These water impairments can then cause eutrophication and harmful algal blooms. For example, the Buffalo Creek Fire from 1996 and the Hayman Fire in 2002 both impacted water reservoirs by increasing sediment loads, which forced local water providers to spend $26 million dollars in dredging to remove the sediment (Hallema et al., 2018).

Wildfire cost to drinking water systems also includes repair of damaged infrastructure, such as pipelines. Infrastructure damages can be easily spotted above ground in pumping stations, but some are hidden in plastic pipes of the distribution system and requires further continuous in-home testing as the toxic chemicals may spread beyond the burned area, and these contaminants may not be so easily detected at the treatment plants (Solomon et al, 2021). Excessive sediment and flood water following extreme precipitation events can also impact water reservoir operations, as well as add stress and difficulties to the water treatment process (George 2022).

Table 1. Examples of case studies' economic loss of drinking water systems to wildfire (Fountain 2021; Orange County, 2008; Proctor et al., 2020; usda.gov, 2017).

Fire Name	**Acres Burned**	**Water Storage Loss**	**Sediment Removal**	**Infrastructure Repair**	**Restoration & Mitigation**
2007 Hayman Fire, CL	138,000	$37 million	$27 million	$7 million	$2 million
2017 Tubbs Fire, CA	36,807			$44 million	$8 million
2018 Camp Fire, CA	153,336			$33 million	
2020 LNU Lightling Complex Fire, CA	363,220			$150 million	
2008 Freeway Complex Fire, CA	30,305			$69 million	
2020 Cameron Peak Fire, CL	208,913	$7.3 million	$30 million	$35 million	
2020 Riverside Fire, Beachie Creek Fire, Holiday Farm Fire, Archie Creek Fire, OR	636,696		$310 million		
2012 High Park Fire, CL	87,284				$24 million

Wildfire also impacts heavily on the disinfection and treatment process of drinking water, and with degrading stream conditions following wildfires, treatment processes become more difficult and expensive. Communities in forested watersheds rely on the natural filtration of upstream processes, but wildfire can increase sediment and nutrient loading, causing poor water quality and potentially shutting down treatment plants (Hohner et al., 2019). The main concerns surrounding treatment plant operations are coagulation, flocculation, sedimentation, filtration, disinfection, and membrane filtration (Pennino et al. 2022). Increased turbidity and suspended solids flowing into treatment plants influence the flocculation process, and the quick buildup of solids in treatment plants will require more frequent mixing, removal, and disposal of solids. Elevated turbidity levels also increase the frequency and decrease the effectiveness of slow sand filtration, causing shorter filter lifespans and more frequent filter replacement. Extremely high turbidity levels often require treatment plants to switch to microfiltration or ultrafiltration membranes (Sham and Ozekin, 2014), which are expensive and require frequent chemical cleaneding. Excessive nutrient and DOC levels often lead to high levels of disinfection by-products in the traditional chlorine disinfection process, and eutrophication and algal bloom can occur. Therefore, removal of dissolved organic matter is required before treatment, or utilizing alternative disinfection techniques such as UV, ozone, and activated carbon to remove nutrient organic matters (Becker 2020).

2.6 Wildfire impacts patterns and recommendations

2.6.1 Land ownership and wildfire severity

Across the Pacific Northwest, managed private lands burned less frequently than non-managed public lands. US Forest Service lands burned more frequently than any other land ownership classes in the past 30 years (Barros et al., 2021). For the four 2020 Oregon fires, this pattern was once again observed, with over 35% of total acres burned being USFS land, and a significant portion of private (19%) and private industrial forest lands (20.2%) burned as well (Figure 2.1a). Land ownership not only impacts forest fuel management, but also firefighting efforts as well, and when combined with vegetation types, may become important predictors of wildfires in the Western US (Starrs et al., 2018). Effectiveness of post-fire land management programs varies across land ownership types, where publicly owned lands are commonly easier to manage in the post-fire restoration process than privately owned lands (Stephens et al., 2020).

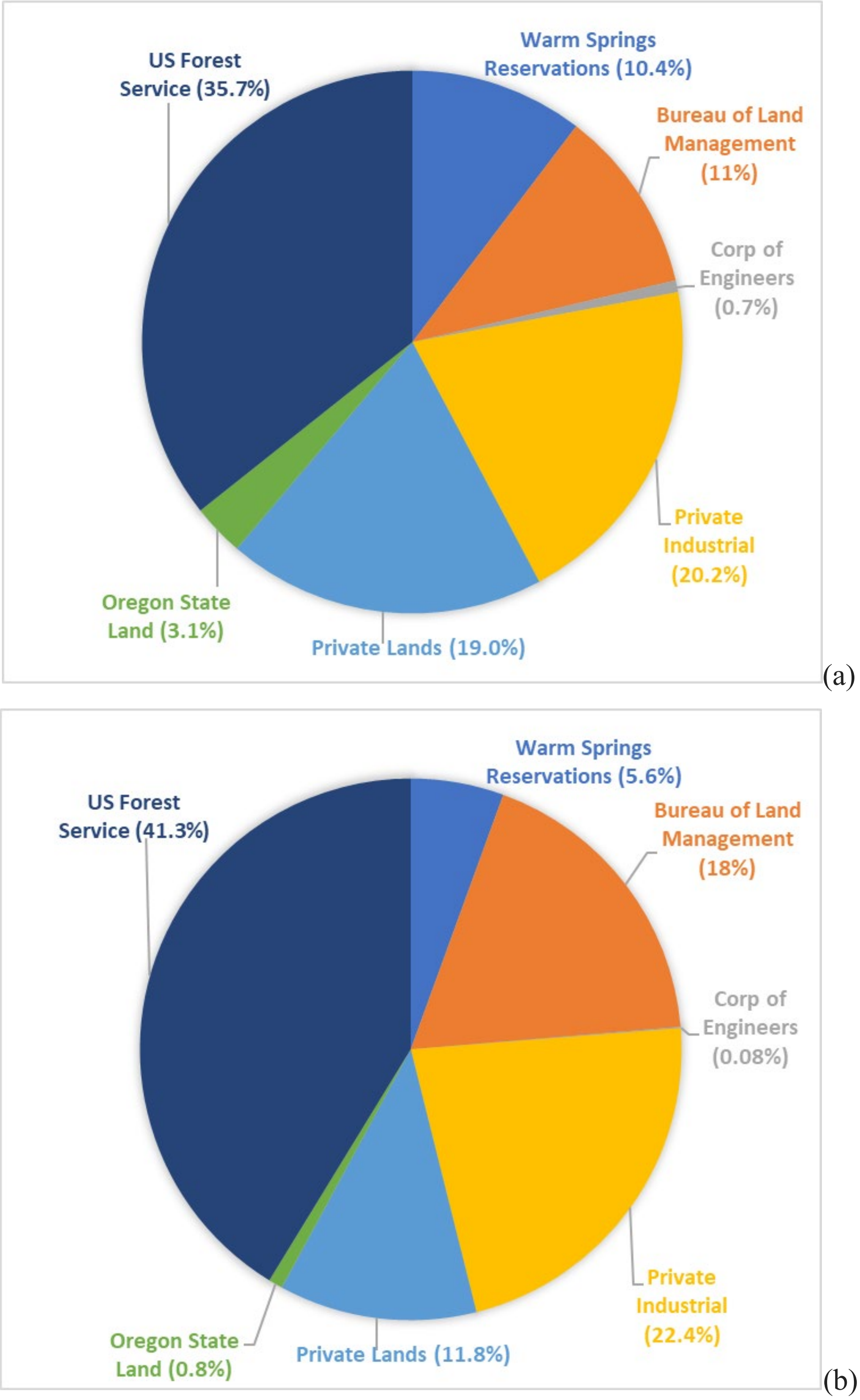


Figure 2.1: Distribution of burn percentage in different land ownership for the four 2020 Oregon fires (a) and distribution of high severity burns in each land ownership (b).

On the other hand, wildfires are potentially land use problems as well, especially when cities expand urban growth boundaries into forested landscapes and install electrical lines. Expanding urban boundaries also increases property loss and risk to human lives in the event of wildfires, as well as toxic chemicals released from burning urban structures (Green 2019). Although publicly owned lands contribute more in total burned areas every year, wildfires are three times more likely to start in privately owned lands. Degrees of fire and forest management activities vary across jurisdiction and land ownership boundaries, and therefore may influence fire severity in addition to forest type and topography. A recent study on the Douglass Complex Fire in Oregon (Zald and Dunn, 2018) found that younger and privately-owned industrial forests burned at a higher severity than older and federally owned forests, due to spatially homogenized continuous fuel arrangement (CRS, 2022).

2.6.2 Recommended Actions

(a) Drinking water supply and treatment

- Upgrade drinking water treatment facilities: Additional modification, treatment technology, disinfection, and maintenance may be necessary to remediate poor source water quality following wildfires.
- Identify toxic substances and organic matter leached into delivery and water treatment systems
- Establish alternate/emergency water supplies that are more resilient to wildfire disturbances, which may include diversifying drinking water sources and increasing underground storage capacity
- Drinking water infrastructure contamination prevention and mitigation following future wildfire events should involve a rapid survey of household faucet contamination and in order to detect the lingering chemicals in the distribution system. Activated carbon filtration devices should be provided to households that experience short-term drinking water pollution.

(b) Risk communication and monitoring

- Effective and prompt risk communications events for residents: Public outreach and education on community response to safe drinking water issues (e.g., testing water quality) following wildfires are key to establishing resiliency (Odimayomi et al., 2021).

- Establish real-time monitoring networks in both public and private lands, continue to monitor and test water quality post-fire for chemical contamination in households
- Forecast-based water reservoir operations to manage intake and discharge systems prior to and following high-intensity storms to minimize risk to drinking water systems.
- Increase water reservoir sedimentation capacity

(c) Sediment erosion control and capture

- Introduce other post-fire erosion reduction practices such as using contour felled logs and compost since erosion barriers were found to be effective at the reach scale to reduce sediment input into streams (Ahn et al., 2013; Crohn et al., 2013).
- Enhance stream structures and retention ponds to capture sedimentation during storms
- Identify key treatment areas pre- and post-fire for erosion control and ash filtration
- Identify key riparian areas that are more vulnerable to wildfire impacts and establish structures to minimize stream bank erosion (e.g., erosion control fence)
- Avoid salvage logging in critical areas to minimize sediment erosion

(d) Land management and policy

- Regularly monitor electrical power lines in forest lands to avoid any potential source ignition
- Diversify forest species and ages in industrial forest lands to reduce high intensity burned areas
- Human-assisted forest successional recovery tools should be implemented, such as native tree planting, woody debris placement to increase habitat complexity, and erosion control with mulching
- The implementation of nature-based solutions such as beaver dams can reduce burning in source regions and filter ash and other post-fire pollutants and prevent them from entering downstream waterways (Whitcomb 2022)
- Develop new regulations for land development zoning, and require flammable homes and structures to be built with a buffer of at least 200 feet, remove and maintain a buffer of vegetation free, “home ignition zone”

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