THE EFFECT OF FIRE ON FOREST SOILS AND HYDROLOGIC RESPONCES: A REVIEW

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ABSTRACT

The goal of this review was to investigate the correlation of wildfires with decreased infiltration and increased runoff. Research suggested that wildfires can alter several forest soil properties affecting infiltration and runoff, including the formation of a fire-induced water repellent layer, the addition of a surface ash layer, and the removal of surface cover. The combination of these effects can lead to serious hydrologic and geomorphic events such as flooding, large-scale erosion and water sedimentation problems. The pre-fire soil condition is a determining factor to the overall influence of the fire, in particular, soil moisture content and amount of soil organic substances. Soil moisture content can either promote heat transfer or prevent extreme high temperatures depending on its level. Soil temperature combined with the amount of soil organic substances determines the strength of the fire-induced water repellent layer within the soil profile. Ash was found to have somewhat contradicting short-term effects with respect to infiltration and runoff. It is either seen as a natural way of mitigating water repellency and loss of surface cover by increasing infiltration capacity and protecting underlying mineral soil from raindrop impact. However, some studies also suggest that it adds to reduced infiltration by causing soil sealing. The case study from South Interior Forest Region of British Columbia describes a Risk Analysis report for the Sitkum Creek Fire (number N70347) in 2007 that includes useful management strategies developed to mitigate the effects of wildfire in community watersheds.

KEY WORDS: forest fire, forest soils, water repellent soil, runoff, infiltration, ash

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1.0 INTRODUCTION

Wildfires present a continuous concern for land managers with respect to how they alter soil conditions and subsequent hydrologic responses. There is strong evidence that the correlation between wildfires and major flood events is more than a coincidence. Some studies suggest that the creation of a water repellent soil layer is the most significant cause of this, while others weigh importance upon the loss of surface cover and the addition of an ash layer {{53 L.F,DeBano 2000; 33 Larsen,IJ 2009;}}. Even still, it is unclear whether or not an ash layer helps to counter act the hydrophobicity, or adds to the concern of reducing infiltration {{36 Onda,Yuichi 2008;}}.

This review aims to expose the link between characteristics of fire-induced water-repellent soils and hydrologic responses that could be lead towards flood and mass erosion events. By understanding this relationship, one might be able to predict and mitigate the hazard of floods erosion and sediment yields following a severe fire. Therefore, the goal of this review is to better understand the relationship between wildfires, soils, hydrology, erosion and sediment transport. This review is organized into three sections (1) background information on the process of creating fire-induced water repellent layer in soils, (2) post-fire effects of hydrologic responses, and (3) mitigation practices from a specific case study in BC.

2.0 THE EFFECT OF FIRE ON SOILS

Severe wildfires can burn vast areas leaving behind an altered landscape. After a fire, most of the vegetation is gone and the charred soil is covered in a layer of ash. Despite this, fire resistant species such as Douglas-fir *(Pseudotsuga menziesii)* and other types of vegetation protected by streams and ponds are able to actually survive severe fires. However, fires are not always severe enough to cause this much damage to an ecosystem. In fact, some ecosystems have successfully evolved and are specially adapted to frequent low severity fires. In this case, fires can rejuvenate ecosystems bringing new life and reducing competition for native species. For example, they shape ecosystems in respect to specific vegetation reproduction methods that allow some plants to quickly re-establish themselves after a fire by using the heat produced during the fire to break open and release seed cones. This section will discuss how fires are rated and the process of creating a fire-induced water repellent layer.

2.1 FIRE INTENSITY AND DURATION

Each fire has its own rating of intensity and duration. Intensity is described by Certini (2005) as the rate at which a fire produces thermal energy. A key factor in determining the transfer of heat is the amount of moisture present in the soil. Fires transfer heat faster and deeper through moist soils than dry soils. In all circumstances, heat energy exploits soil water or moisture as an easy and efficient mode of transportation. This is analogous to an electrical current that travels over wet skin, as opposed to internally through your body. This occurs because the surface moisture provides a convenient path of least resistance. In a wildfire, even though moist soils transfer heat easily, they will have a lower temperature compared to dry soils, assuming all other factors are equal. This is because as fire burns in a moist soil, latent heat is released as soil water is vaporized and this release of energy results in lower sensible heat measured as soil temperature {{26 Certini,Giacomo 2005;}}. In dry soils, there is less latent heat released since less water is available for vaporization, which allows for sensible heat energy and temperatures to rise. It is at this point that the importance of fire duration comes into play.

Fire duration is the second factor that determines effects on soil. A long-duration fire will result in the greatest below-ground damage since the longer the fire burns, the more opportunity it has to evaporate soil moisture, increase soil temperatures, and burn deeper into the soil profile {{26 Certini,Giacomo 2005;}}. In this case, temperatures can remain high for several days after the fire as it continues to smoulder beneath the soil surface. In contrast, heat from an intense, but fast-moving, fire only has the chance to penetrate the soil a few centimeters before it moves on. This type of fire would result in less below-ground damage, but is usually driven by strong winds that can direct the fire vertically up into the tree canopy or horizontal across the land.

2.2 FORMATION OF A WATER REPELLENT LAYER

Typically, fire-induced soil hydrophobicity is formed as a discontinuous water-repellent layer of varying thickness located 6-8cm below the surface parallel to the mineral soil. Heat activates the vaporization of soil organic substances which then migrate down through the soil profile following the temperature gradient to where they cool, condense and coat mineral particles {{53 L.F,DeBano 2000;}}. The heating causes a chemical bond between hydrophobic organic substances and mineral particles in the soil. Residual heat remaining in the soil can cause particles to re-volatize making the water repellent layer thicker and/or further curing the hydrophobic substances {{55 Savage,S.M. 1974;}}.

Several factors affect water repellency, including the amount of soil organic substances, and soil moisture content, but most important is the maximum soil temperature during a fire. DeBano (2000) studied which temperatures create the greatest hydrophobicity. His results were based on the following three temperature classes: (1) temperatures < 175°C had little change in water repellency, (2) temperatures between 175°C and 280°C result in intense water repellency, and (3) temperatures above 280°C to 400°C actually destroy water repellency. He found that the most efficient way to coat mineral soil particles with volatized hydrophobic substances is to heat the soil at lower temperatures (175°C - 200°C) for shorter periods of time. Heating for longer periods of time at high temperatures would actually destroy organic substances {{53 L.F,DeBano 2000;}}.

Fires can only amplify hydrophobicity because of how they congregate pre-existing hydrophobic substances into a concentrated layer. The process is based on the amount of organic substances present in the soil. Soils with naturally low levels of organic substances would tend to have a weaker, less-established water repellent layer compared to soil with a naturally high organic content.

The extent of soil moisture can either act to promote heat transfer or extinguish it. As described previously, slightly moist soils can conduct heat energy more efficiently throughout a soil than if it was dry. However, if moisture content is high and the soil is wet, temperatures will stay relatively low because the wetness helps soil to resist burning. Variations in moisture content for a particular area at the time can be accounted for by changes in micro topography. Lower mesoslope positions and depressions accumulate subsurface and overland flow which can keep the forest floor and underlying soil more moist than adjacent areas. Differing soil moisture contents contribute to uneven burn severities alternating sections of water-repellent soil with permeable soil {{26 Certini,Giacomo 2005;}

2.3 QUANTIFYING WATER REPELLENCY IN SOILS

Water repellent soils are defined as those into which a drop of water will not spontaneously penetrate {{25 Letey,J. 2001;}}. Water drop penetration time (WDPT) is used to measure small scale soil water repellency. It is based on the theory that a drop of water on a soil's surface will eventually penetrate into the soil column and the measured time it takes to do this is unique for each soil {{25 Letey,J. 2001;}}. The larger the value of WDPT, the longer water takes to penetrate into the soil and the greater the magnitude of water repellency.

Water droplets do not infiltrate into a hydrophobic soil right away, indicating that the water-soil contact angle is equal to or greater than 90°. When hydrophobic soil is exposed to a water droplet it begins to change so that the contact angle reduces to less than 90° {{25 Letey,J. 2001;}}. This is significant because the time it takes for the angle to reduce determines the WDPT and illustrates how quickly water repellency can be transformed once it is in contact with water {{25 Letey,J. 2001;}}. Unfortunately, the techniques described above can only be used to measure soil water repellency at very small scales because at a large scale it would be too difficult to get a representative sample of measurements that account for the high spatial variation of repellency commonly found at the larger scale. {{33 Larsen,IJ 2009;}}.

2.4 DURATION OF WATER REPELLENCY

On average, water repellency can last anywhere between 2 – 6 years, depending on the burn severity and weather conditions before and after the fire. In their technical report, Curran et al. (2006) found that effects of the hydrophobic layer are most pronounced after prolonged dry periods, or shortly after a fire, when the upper soil profile is dry {{56 M.P. Curran 2006;}}. Seasonal weather patterns before, during and shortly after the fire are important indicators to potential impacts of the fire on the landscape because weather patterns will reveal the moisture content history at the site. For example, a well-formed wide-spread water-repellent layer could be more likely if the fire occurs during an extended period of hot, dry conditions with little rain in the following weeks. In that case, soil conditions can be relatively homogeneous over several microsites instead of dry microsites being mixed in with wetter ones. To overcome the barrier of repellency, water uses preferential pathways through macropores and rootways, as well as areas of lower repellency to infiltrate into the soil profile. The best type of rainfall to thoroughly re-wet the soil is one of low-intensity for long periods of time, such as rainfall generated from frontal precipitation. This type of rainfall is efficient at infiltrating water-repellent soils because of the slow rate at which it falls. Slowly, it allows for water to find preferential flow pathways and begin weakening the water repellency without excess rain causing the soil to become saturated to initiating runoff and overland flow. Understandably, soils with a higher degree of repellency are required to be wetted more thoroughly throughout the soil column to restore it to a pre-burned state. Curran et al. (2006) also found that water repellency weakens through time when watersoluble hydrophobic substances start to break down, in combined with post-fire site rejuvenation such as the forest floor building up.

2.5 NATURALLY OCCURRING HYDROPHOBICITY

Soils with naturally high levels of hydrophobicity in upper soil horizons react differently to fire than soils originally lacking natural hydrophobicity. Specifically, if sites with naturally-occurring hydrophobicity experience wildfire, the relative change in hydrologic effects will likely be considerably less due to their pre-existing tendencies towards water repellency. DeBano's review (2000) provides three ways that hydrophobicity can naturally occur in upper soil horizons. First is when partially decomposed organic matter mixes and dries with mineral soil. Second, is when decomposing plant parts from the soil surface are leached into the soil. Finally, hydrophobicity can result from fungal growth in organic-rich upper soil horizons {{53 L.F,DeBano 2000;}}. Consistent with these observations,

Varela et al. (2005) studied water repellency in south western Spain and outlined characteristics of unburned sites that would be conducive to natural high water repellency. They found sites often have either (1) trees with lots of resin, wax and aromatic oils, such as eucalyptus and pine; (2) a temperate-humid climate containing lots of organic matter and thick litter layers with a drying period of 1-3 months allowing for the soil to exist close to wilting point; or, (3) strongly acidic soils with significant amounts of fungi and soil biomass, mor humus and low solubility of organic compounds {{38 Varela,M.E. 2005;}}.

Doerr et al. (2005) studied high natural water repellency in soils of eukalypt forest catchments near Sidney, Australia to see how post-fire soil effects are different from soils without high natural water repellency. The research supports that naturally high water repellent soils are altered differently as they burn than soils that lack natural water repellency. They found that on sites that hadn't experienced burning for a long time, there was severe to extreme water repellency at the soil surface and slight to moderate repellency for the subsurface, signifying an overall high level of repellency {{37 Doerr,S.H. 2005;}}. Doerr et al. (2005) note that burning caused extensive reduction of repellency in these soils. Burn severity determined the depth of the effect, generally ranging from 0.5- 5cm {{37 Doerr,S.H. 2005;}}. They also found that soil below the newly charred wettable layer did indeed increase in repellency because it was deep enough that the soil heat gradient had reduced and remained intact {{37 Doerr,S.H. 2005;}}. Even though the eukalypt forest did not increase in water repellency overall, it is still at risk to other associated post-fire hydrologic impacts similar to other burned sites. Researchers and managers alike are most concerned with wildfires on sites with little natural water repellency as they can result in radical changes to hydrologic processes with the general understanding being that infiltration decreases, lead to greater runoff and, erosion.

3.0 THE EFFECT OF FIRE ON HYDROLOGIC RESPONSES

Fire-induced water repellency, loss of surface cover and the addition of an ash layer can cause major changes in hydrologic processes with respect to infiltration, runoff, and soil sealing. These factors interrelate to characterize the soil after a burn for a particular site. Each site reacts differently to the combination of soil changes. This section will investigate the effects that water repellency, ash, and reduced surface cover can have on infiltration, runoff and soil sealing.

3.1 THE FUNCTION OF WATER REPELLENCY ON INFILTRATION AND RUNOFF

Fire-induced soil water repellency is a form of modification to the soil that affects the ability of water to infiltrate into the soil, as well as how the soil controls and influences surface runoff. Infiltration is the process by which water enters soil pore spaces and becomes soil water {{58 Brady, Nyle C. 2004;}}. Infiltration capacity is the rate that which a defined volume of water can enter the soil per unit time {{58 Brady, Nyle C. 2004;}}. It is influenced by soil saturation capacity, defined as the amount of water that can be stored within the soil. As water infiltrates, it first satisfies the soil moisture deficit of the pre-precipitation state of the soil and then begins to travel through the soil. Key factors affecting a particular soil's infiltration rate are associated with the physical makeup of the soil, such as soil texture and presence of any soil layers that restrict downward movement of water, like a water repellent layer {{58 Brady, Nyle C. 2004;}}. Soil texture describes the relative proportions of sand, silt and clay in the soil {{58 Brady, Nyle C. 2004;}}. The composition and arrangement of particles influences the amount and size of pore space throughout the soil which helps determine how easily water can infiltrate and its saturation capacity. For example, uncompact soils comprised of larger particles with greater pore space provide conditions suitable for easy infiltration. Once water infiltrates, it can continue to move down the soil profile by way of percolation. Infiltration rates are important because they determine how water behaves at the soil surface. For the coarse-textured soil described above, infiltration is rapid and water quickly percolates into the soil and moves via subsurface lateral flow. In contrast, slow infiltration allows for more water to accumulate on the soil surface to be available for evaporation or surface runoff, which can lead to erosion.

There are several differences between infiltration rates between normal wettable soils and water-repellent soils. DeBano (2000) outlines that results from experiments on soils with uniform water repellency indicate that infiltration is slowest initially and increases with time. In contrast, a normal wettable soil initially has fast infiltration rates that decrease with time as the soil becomes more saturated. In addition, moist soils with uniform water repellency have faster infiltration rates than dry soils {{53 L.F,DeBano 2000;}}. For soil with a water-repellent layer below a thin layer of wettable soil, infiltration is complex. Initially, water is able to infiltrate easily through the wettable soil until it meets the water-repellent layer. At this point, infiltration rapidly decreases as water slowly seeps through the repellent layer into the underlying wettable soil. Below the repellant layer, infiltration rates can increase again {{53 L.F,DeBano 2000;}}.

Runoff rates are directly influenced by infiltration and soil saturation capacity that defines the amount of water that can be stored within the soil. A layer of water repellency below a section of wettable soil (6-8cm deep) temporarily acts like a false bottom to the soil profile. The effect of this is most drastic during short periods of intense rainfall when it is unlikely for infiltration to have enough time to penetrate through the water repellent layer before saturation capacity is met. Once the upper wettable layer reaches saturation capacity, excess water becomes runoff contributing to overland flow {{53 L.F,DeBano 2000;}}. The threshold at the boundary between the wettable soil and the underlying water repellent layer is prone to erosion and sliding when the saturated wettable soil becomes loosely attached to the soil beneath. This process is much like how avalanches develop when the snowpack contains layers with variable physical properties.

3.2 THE FUNCTION OF ASH ON INFILTRATION AND RUNOFF

Water repellent layers prove to be influential in post-fire hydrologic effects, but they do not act alone. A surface layer of hydrophilic ash is created from combusted material settling to the forest floor during fires. This layer is thought to be responsible for several short-term changes like soil sealing, increased infiltration capacity and pore clogging that affect infiltration and runoff {{33 Larsen,IJ 2009;}}.

Larsen et al. (2009) describe soil sealing as the development of a thin (0.1-1.0 mm), dense soil layer at the mineral soil surface that has hydraulic conductivity that is several orders of magnitude lower than the underlying soil {{33 Larsen,IJ 2009;}}. A review by Assouline (2004) outlines the two types of seals, structural and depositional or sedimentary seals, and the processes involved in seal formation. Structural soil seals are developed at the soil surface when fine material is created from the destruction of soil aggregates in response to raindrop impact, compaction, slaking, or particle segregation{{57 Assouline,S. 2004;}}. The most common process is raindrop impact breaking apart soil aggregates at the surface. In this case, coarser material is washed away by runoff while finer material settles into the soil below, filling pore spaces and compacting soils that could otherwise contribute to infiltration {{57 Assouline,S. 2004;}}. Depositional seals form when fine particles are carried in suspension by runoff then create a thin dense layer at the surface where they settle {{57 Assouline,S. 2004;}}. This type of seal is not as strong as structural seals because it is not formed due to compaction {{57 Assouline,S. 2004;}}.

Results from experiments and research on ash effects on soil-water processes show a variety of effects. For example, some studies suggest that ash has the tendency to clog pores, causing soil sealing {{12 Onda,Yuichi 2007;}}, while others argue that ash helps absorb rainfall and protects the mineral surface from raindrop impact and soil sealing {{33 Larsen,IJ 2009;}}. Larsen et al. (2009) preformed a series of ash-manipulation experiments to try to decipher post-fire ash effects. They concluded that the most important feature of ash is its ability to prevent soil sealing {{33 Larsen,IJ 2009;}}. In support of this conclusion, they observed a delay in the onset of runoff for sites with an ash layer. Furthermore, the observed volume of runoff was only about half the value of the calculated theoretical runoff volume. Larsen et al. (2009) attributed this difference to the fact that when exposed to rainfall impact, ash is quickly compacted and eroded, which reduces its porosity and the volume of water it can store. Nevertheless, they found that ash cover can protect against soil sealing and reduce runoff rates {{33 Larsen,IJ 2009;}}. Even though ash proves to be helpful in mitigating the soil environment after burning, the benefits are short term and only last through the first couple of precipitation events {{33 Larsen,IJ 2009;}}. Wind, water and raindrops easily destroy ash through dispersion or compaction which weakens its ability to protect the underlying soil and absorb water {{33 Larsen,IJ 2009;}}.

A similar analysis by Onda et al. (2008) investigated the role ash has on post-fire soil hydrology, but assessed the difference in effects from during the first rain storm after fire relative to subsequent storms. They found that during the first storm, rainfall infiltrated to the base of the ash layer where it encountered greater hydrophobicity and decreased infiltration, causing subsurface flow and some overland flow via preferential flow pathways through the ash layer {{36 Onda,Yuichi 2008;}}. However, repeated rainfall events resulted in the ash layer to erode, compress, clog pores and crust on the surface, which hinders the ability for rainfall to infiltrate the soil{{36 Onda,Yuichi 2008;}}. Consequently, Hortonian overland flow became the prominent form of runoff and produced a high overland flow-runoff rate {{36 Onda,Yuichi 2008;}}. Onda et al. (2008) recognize that their runoff results are different than those observed in South Africa by Mills and Fey (2004) who studied how burning made soils more apt to surface crusting and found that overland flow brought significant rill formation instead of Hortonian overland flow. Rills form when soil material is transported by surface runoff then accumulates in channels at the base of steep slopes and remains there until stronger stream flow carries it further downstream {{53 L.F,DeBano 2000;}}. Onda et al. (2008) speculate that the differences in overland flow between studies may be due to site differences since Mills and Fey's (2004) severely-burned granitic sites had a 10-20cm deep hydrophobic layer{{36 Onda,Yuichi 2008;}}. Having such a deep hydrophilic layer meant there was a thicker wettable layer near the surface which provided more easily erodible material.

3.3 THE FUNCTION OF SURFACE COVER LOSS ON INFILTRATION AND RUNOFF

Surface cover of vegetation is an important factor contributing to the hydrologic cycle or water cycle (Fig. 1). Severe wildfires have a significant impact on the cover of living trees, standing dead trees, downed wood, understory vegetation and litter on the forest floor. The sudden change and in forest structure and loss of canopy cover, together with the addition of a water-repellent soil layer and ash spur changes in the hydrologic cycle that could lead to potentially hazardous runoff and erosion levels. The remainder of this section will investigate the role of fire-induced surface cover loss with respect to runoff and erosion

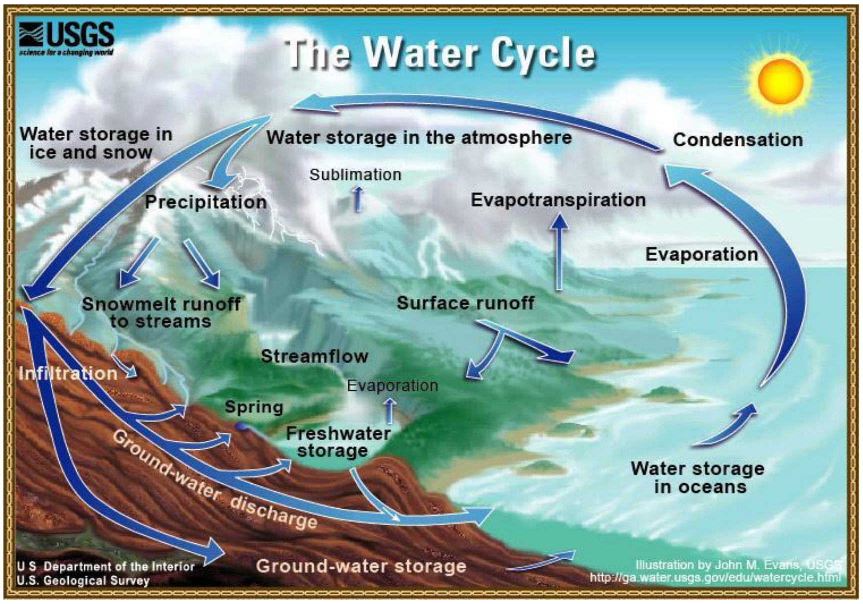

Figure 1: The water cycle (United States Geological Survey)

The hydrologic cycle illustrates the movement of water and water vapour from the atmosphere, to its behaviour on the earth's surface and how some of it returns to the atmosphere {{58 Brady, Nyle C. 2004;}}. Trees and forest ecosystems play a pivotal role in how water moves throughout the system, affecting both liquid water and water vapour movement. As rain falls it is either intercepted by the vegetation including the forest canopy, falls through the canopy to the ground, or lands in a body of water. Precipitation intercepted by the forest canopy is prevented from reaching the surface and becomes available for evaporation back to the atmosphere. Precipitation that makes its way through the canopy or directly lands on the forest floor is called "throughfall". The forest floor and duff layer acts as a buffer to protect the mineral soil from the physical impact of throughfall, preventing or reducing surface soil erosion {{56 M.P. Curran 2006;}}. In addition, forest floors are porous and have the ability to hold significant amounts of water then slowly release it into the mineral soil {{56 M.P. Curran 2006;}}.

Since fires reduce the amount of surface cover, including the canopy, understory vegetation and litter of the forest floor, they allow for more precipitation to reach the burned soil surface. The amount of forest floor consumed by a fire depends on its severity. Less severe fires may not completely consume the forest floor, allowing it to still provide benefits such as limiting the risk of erosion and runoff and acting as insulation for the mineral soil against heat from the fire{{56 M.P. Curran 2006;}}. In contrast, a high-severity fire would substantively reduce the cover of litter on the forest floor. This results in increased surface runoff and erosion {{56 M.P. Curran 2006;}}. Eroded materials are carried by overland flow as they are transported within a watershed via channels and gullies as they make their way to streams {{56 M.P. Curran 2006;}}. Overland flow carrying suspended sediments continue to erode channel beds and banks, increasing the sediment yield transferred downstream to alluvial fans {{56 M.P. Curran 2006;}}. The risk of large-scale erosion, flooding or debris flows is increased on sites experiencing heavy rain, soil erosion, overland flow, and high sediment yields following fire.

4.0 MANAGEMENT AND MITIGATION OF POST-FIRE SOIL EFFECTS

The Southern Interior Forest Region of BC has a well-developed Forest Sciences Section that has studied and recorded the post-fire effects on BC watersheds for various past fires with regards to risk assessments and management strategy recommendations. In particular, an assessment team has published a Post-Wildfire Risk Analysis report for the Sitkum Creek Fire (number N70347) in 2007. The Sitkum Creek fire will be used as a case study since the report describes in detail the extent and severity of the burn, associated risks and hazards, as well as recommended mitigation and management practices tailored towards the Sitkum Creek area.

The Sitkum Creek Watershed is 27 km^2 located on the north side of the West Arm of Kootenay Lake. From July 27th to mid-August an area about 1075 hectares burned during the fire which included about 39% of the Sitkum Creek watershed. It was reported that the area contained 10% high vegetation burn severity, 11% moderate vegetation burn severity, 50% high vegetation burn severity on some small tributaries and also high widespread soil burn severity and water repellency {{59 Jordan, Peter 2007;}}. The burn severity classification of the Sitkum Creek fire describes the effects of the fire on the forest canopy and understory, as well as the effects of the fire on soil hydrologic functions. Vegetation burn severity is classified as the following {{56 Curran 2006;}}:

- High- trees blackened and dead, needles consumed, understory consumed;
- Moderate- trees burned and dead, needles remain, understory mostly burned;
- Low- canopy and trunks partially burned, understory lightly or patchily burned.

Soil burn severity and water repellency is classified as the following {{56 Curran 2006;}}:

- High- forest floor consumed, mineral soil has altered porosity and structure;
- Moderate- litter consumed; duff consumed or charred, mineral soil unaltered;
- Low- litter scorched or consumed duff and mineral soil unaltered.

Due to the location of the fire and its spatial proximity within the Sitkum Creek watershed, there are several resources at risk and hazards created due to the extent of the burn. Jordan et al. (2007) outlines factors that are at risk of possible post-fire hydrologic or erosional events, they include {{59 Jordan, Peter 2007;}}:

- Public safety, houses, and private land on the Sitkum Creek alluvial fan;
- Highway 3A, bridge, secondary roads, and utilities on the fan;
- Water quality in Sitkum Creek; and
- The community water intake and other smaller water intakes on Sitkum Creek.

Hazards created in response to the fire involving post-fire hydrologic or geomorphic changes to the area include {{59 Jordan, Peter 2007;}}:

- The addition of a water repellent layer which reduces infiltration and could result in overland flow during heavy rainfall;
- Loss of litter and duff layers which reduces the water storage capacity of the forest floor;
- Loss of forest canopy and understory shrub layer which reduces the interception capacity;
- Loss of vegetation and forest floor layers which increases the raindrop energy impacting the underlying mineral soil that exposes the mineral soil to a greater chance of erosion; and
- Loss of forest vegetation which reduces the amount of evapotranspiration, increases snow accumulation, and potentially higher groundwater levels.

Short-term hazards, such as increased streamflow, soil erosion, debris flows, are most likely to occur within the next 3 to 5 years {{59 Jordan, Peter 2007;}}. They are brought on by certain trigger events like short-duration, high-intensity summer rainstorms, or long-duration frontal rainstorms in the fall or winter {{59 Jordan, Peter 2007;}}. Also the fact that the Sitkum Creek is a community watershed with a well-developed alluvial fan means that there is additional risk of avulsion to the creek channel and water quality concerns brought on by increased sedimentation in the creek {{59 Jordan, Peter 2007;}}.

In response to the recognized risks and hazards, Jordan et al. (2007) has identified several management activities designed to reduce the hydrologic and geomorphic impact of the fire on the surrounding Sitkum Creek watershed. They are listed as the following in the report prepared by Jordan et al. (2007) {{59 Jordan, Peter 2007;}}:

1. Communicate information on the post-fire hazards and risks to stakeholders, including local residents, landowners, and owners of the local mine.
2. Update the 1990 study on alluvial fan hazards to represent the changed conditions in the watershed post-fire. This should include the return periods of floods on the Sitkum Creek fan, channel and highway bridge capacity to manage the expected floods and debris flows, as well as fan improvements and flood preparedness.
3. Apply mitigation treatments, such as aerial mulching, used to reduce debris flow hazard at tributary streams.
4. Deactivate the Sitkum-Alpine road in order to reduce stream sedimentation resulting from debris flow or erosion events.
5. Reforest vegetation cover to help restore previous hydrologic conditions.
6. Develop a watershed risk mitigation and restoration plan, including a communications plan, to ensure activities are coordinated.
7. Apply hydrologic models to assess the post-wildfire hydrologic changes to Sitkum Creek to produce better estimates of probable streamflow.

8. Monitor streamflow and water quality on Sitkum Creek for several years, or until substantial recovery of hydrologic processes has occurred, as well as monitoring discharge volumes to better forecast high flood levels.
9. Inspect mill site and mine waste for possible sources of contamination that might be affected by the fire or post-fire flooding.
10. Map burn severity using Landsat imagery for both pre-and post-fire states.
11. Acquire high-resolution satellite imagery, or aerial photography to use as a reference for planning reforestation and monitoring post-fire erosion events and recovery.
12. Monitor rainfall, erosion events, revegetation, and the effectiveness of any mitigation treatments in the burned areas for several years, to assist with assessment or risks on the fan, and to improve the understanding of post-fire hydrologic processes

5.0 DISCUSSION

This review uses several sources to compile major patterns about the effect of fire on forest soils. Relationships can be drawn from patterns that connect ideas, while at the same time exposing inconsistencies and loose ends within the research. In addition, the resulting risks and consequences of fire on hydrologic processes cause the entire subject to at the attention of researchers and landowners alike.

One such relationship that connects common ideas is that it requires a combination of various interacting factors to cause post-fire landscapes to be more apt to increased runoff and erosion. This begins with certain characteristics of the site itself, such as amount of soil organic substances and available fire fuel, to local weather conditions which determine the pre-fire soil moisture content which influences the temperature of the fire. After the fire, the timing and extent of precipitation in the area contributes to the longevity post-fire soil effects, including the strength of the water repellent layer. Furthermore, the degree of spatial variation of these factors revels how continuous or discontinuous the effects will be across the landscape.

The most prominent inconsistency found within the research revolves around the function of ash on infiltration and runoff. In some cases, ash is thought to clog pores and cause soil sealing {{12 Onda,Yuichi 2007;}},while other research supports that ash increases infiltration capacity and protects soil from raindrop impact and soil sealing {{33 Larsen,IJ 2009;}}. Whatever the effect may be, it will be short lived as ash is easily eroded by water, rainfall, and wind.

It is also important to note that research uses small-scale field experiments to test and observe the effects of fire on forest soils then develop concepts to represent the findings on a larger landscape scale. Larsen et al.'s (2009) paper identifies three fundamental problems that arise when extrapolating observations and results from a small scale to a much larger one, such as a watershed. First, there are no techniques to directly measure soil water repellency at larger scales. Second, the degree of post-fire soil water repellency is very time dependent to changes in soil moisture and to what extent water repellent compounds have been eroded. Third, the water repellent layer will often be quite discontinuous horizontally, meaning that some areas could have high infiltration rates while others in the vicinity are very low {{33 Larsen,IJ 2009;}}. However, even though these small scale observations may not be able to represent the entire watershed exactly, they are able to provide useful insight to effects that may reflect portions of the watershed.

Continued research on this topic will provide land managers with increased insight into the correlation between fire and severe hydrologic or geomorphic events such as flooding and erosion. Awareness of how fire alters different soil properties is vital to developing successful management and mitigation strategies used to combat the risks and hazards to public safety, infrastructure and to the natural landscape especially when concerned with sedimentation in watersheds.

REFERENCES

Assouline, S. 2004. Rainfall-induced soil surface sealing: A critical review of observations, conceptual models, and solutions. VADOSE ZONE JOURNAL **3:** 570-591.

Brady, N.C., and Weil, R.R. 2004. Elements of the Nature and Properties of Soils. 2nd ed. Pearson Education, Inc, Upper Saddle River, New Jersey USA.

Certini, G. 2005. Effects of fire on properties of forest soils: a review. Oecologia **143:** 1-10.

DeBano, L.F. 1981. Water repellent soils : a state-of-the-art. United States.

Doerr, S.H., Shakesby, R.A., Blake, W.H., Chafer, C.J., Humphreys, G.S., and Wallbrink, P.J. 2005. Effects of differing wildfire severities on soil wettability and implications for hydrological response. Journal of Hydrology **319:** 295-311.

Fox, D.M., Darboux, F., and Carrega, P. 2007. Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions. Hydrol. Process. **21:** 2377-2384.

Jim Schill. 2001. Fire and flooding in Los Alamos: Pipe ramming provides a solution. Water Eng. Manage. **148:** 13.

Jordan, P., Gluns, D., Covert, A., and Curran, M. 2007. Sitkum Creek Fire, 2007, N70347 Post-Wildfire Risk Analysis.

L.F, D. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology **231–232:** 195-206.

Larsen, I., MacDonald, L., Brown, E., Rough, D., Welsh, M., Pietraszek, J., Libohova, Z., Benavides-Solorio, J., and Schaffrath, K. 2009. Causes of Post-Fire Runoff and Erosion: Water Repellency, Cover, or Soil Sealing? Soil Sci. Soc. Am. J. **73:** 1393-1407.

Letey, J. 2001. Causes and consequences of fire-induced soil water repellency. Hydrol. Process. **15:** 2867-2875.

M.P. Curran, B. Chapman, G.D. Hope, and D. Scott. 2006. Large-scale erosion and flooding after wildfires: understanding the sil conditions. BC Min. For. and Range Res. Br., Rep. 030.

MacDonald, L., and Huffman, E. 2004. Post-fire soil water repellency: Persistence and soil moisture thresholds. Soil Sci. Soc. Am. J. **68:** 1729-1734.

Onda, Y., Dietrich, W.E., and Booker, F. 2008. Evolution of overland flow after a severe forest fire, Point Reyes, California. Catena **72:** 13-20.

Savage, S.M. 1974. Mechanism of Fire-Induced Water Repellency in Soil1. Soil Sci. Soc. Am. J. **38:** 652.

Shakesby, R.A., and Doerr, S.H. 2005. Wildfire as a hydrological and geomorphological agent. Earth-Sci. Rev. **74:** 269-307.

Shakesby, R.A., Doerr, S.H., and Walsh, R.P.D. 2000. The erosional impact of soil hydrophobicity: current problems and future research directions. Journal of Hydrology **231:** 178-191.

Varela, M.E., Benito, E., and de Blas, E. 2005. Impact of wildfires on surface water repellency in soils of northwest Spain. Hydrol. Process. **19:** 3649-3657.