

Post-wildfire Natural Hazards Risk Analysis in British Columbia

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ABSTRACT

Following a wildfire, the chances of soil erosion, floods, and landslides increase, and resultant damage downslope and downstream of the area burned may be catastrophic. This handbook describes the process of assessing change following wildfire, together with an evaluation of downslope and downstream risks to life, property, and infrastructure, or “elements at risk.” The process described will help professionals adapt their knowledge and experience to post-wildfire natural hazard risk analyses. The minimum set of background data, field reviews, and other information that should be included in

all assessments is described. Assessing and mapping soil burn severity is the important first step in any analysis, forming the basis for subsequent soil erosion, hydrology, and geomorphic hazard assessments. The last step, determination of partial risk for each hazard and element, is broadly described. Five British Columbia fire case studies illustrate the application of the procedure. Risk treatment options are discussed; emphasis is placed on upgrading of road drainage structures and slope treatments, especially mulching.

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1 INTRODUCTION

1.1 Background

On average, 2000 wildfires, affecting nearly 100 000 ha, occur annually in British Columbia. Most of these fires burn across forest land. The immediate threats from wildfire include loss of life, property, infrastructure, and timber resources. However, even after a fire is controlled, changes in forest cover, ground surface conditions, and hydrologic processes can result in ongoing risks downslope and downstream of the area burned. The chance of soil erosion, floods, landslides, and snow avalanches (termed “natural hazards”) increases, and the damage associated with these events may be catastrophic. Experience in the western United States and in British Columbia has shown that the assessment of change following wildfire, together with an evaluation of downslope and downstream risks, are the first steps in preventing further post-fire disasters. This Land Management Handbook describes the process of conducting such an assessment and determining associated risks to life, property, and infrastructure. The intent of this document is to guide professionals, experienced in field assessments of forest soils, hydrology, and slope stability, in adapting their knowledge to post-wildfire situations.

In British Columbia, post-fire erosion, floods, and landslides were investigated only infrequently prior to 2003. Several small debris flows and debris slides were reported following the 1973 Eden Fire near Salmon Arm, but few details are available. Changes in streamflow were documented 5 and 10 years after this fire (Cheng 1978; Cheng and Bondar 1984). Elsewhere in the British Columbia Interior, there are only anecdotal accounts of isolated, small post-fire events, and reports in government files of forest road washouts (K. Turner, pers. comm., Oct. 2007). Some interface fires (those adjacent to urban areas or rural populations) were also recognized as having potential post-fire threats to safety because of landslides, and to drinking water. These threats resulted in the first known detailed post-wildfire analysis in British Columbia, completed after the 1998 Silver Creek Fire near Salmon Arm (Winkler 1998). The lower rate of documentation of post-wildfire risk events in Canada compared with the western United States (Cannon and DeGraaf 2009; Moody and Martin 2009) is likely because typical soil burn severities are

lower in more northern latitudes and most Canadian wildfires occur in more remote, less populated areas (Jordan and Covert 2009).

The severe wildfire season of 2003 included several large interface fires. Following these fires, short-duration, high-intensity, or prolonged rainstorms initiated major landslides, such as that at Kuskanook Creek near Creston (Figure 1), and floods that caused significant damage to, or concern over, public safety and/or infrastructure (Jordan et al. 2006; Jordan and Covert 2009). In several other wildfire areas, similar events were relatively minor or of low consequence.

Government, consulting engineers, and scientists involved in assessing the post-wildfire damage recognized the need for a more systematic approach to assessing risks because:

- there was an increased threat to public safety due to post-wildfire hazards,
- there was no existing legal or regulatory mandate to deal with potential hazards,
- professionals were now aware of the hazards and had a professional obligation to act, and
- information about potential risks sent to various agencies and local governments after the 2003 fires garnered a mixed response.

In addition, Filmon’s (2004) review of the 2003 fires included the recommendation that “The provincial government, in partnership with local government, should examine watershed restoration as soon as possible, to identify the areas of severe watershed destruction and develop a plan for the protection and rehabilitation of these areas.” The provincial government agreed to implement all of Filmon’s (2004) recommendations, and a special investigation on post-fire site rehabilitation by the Forest Practices Board (2005) mentioned the lack of defined responsibilities in managing the increased risk from natural hazards.

Consequently, scientists and engineers in the B.C. Ministry of Forests Southern Interior Region began the process of developing a formal “risk analysis” procedure for post-wildfire natural hazards—soil erosion, floods, landslides, and snow avalanches. Field procedures were tested on candidate fires from 2004 to 2006. A first draft technical document (Dobson Engineering 2007) was produced and forms the



FIGURE 1 *Deposition zone of a debris flow that originated from the 2003 Kuskanook Fire, north of Creston, B.C. The fire burned in 2003, and the debris flow occurred in August 2004 during a high-intensity rainstorm. (Photo: P. Jordan)*

basis of the current procedure. The British Columbia procedure was developed with input from U.S. professionals familiar with the U.S. Burned Area Emergency Response (BAER) process (USDA Forest Service 2013).

The BAER process is an emergency risk management response to identifying and managing post-wildfire threats. BAER has the broad objectives of protecting life, property, water quality, critical natural or cultural resources, and deteriorated ecosystems from further damage after a wildfire is out (USDA Forest Service 2013). The program has specific objectives of identifying significant post-fire threats and taking immediate action to manage unacceptable risks. The BAER process follows multiple steps that generally include: mapping soil burn severity; planning, obtaining funding for, and implementing cost-effective treatments that will substantially reduce the risk; and monitoring treatment effectiveness. The BAER begins during or shortly after

wildfire containment, and a report is completed within 7 days of the containment date. An interdisciplinary team of professionals that generally includes hydrologists and soil scientists, and may also include geologists, botanists, cultural resource specialists, engineers, wildlife and fisheries biologists, recreation specialists, and others, is formed to complete the assessments, which range from simple to complex.

The BAER process has been used in the United States for decades, and was recognized by Southern Interior experts as a possible starting point for a British Columbia emergency response process. The modified British Columbia approach focusses primarily on public safety and infrastructure and provides a co-ordinated response at considerably less expense and resourcing than the BAER process. There is also less emphasis on post-fire rehabilitation unless the assessment indicates that the risk is high and that treatments can be considered cost- and operationally effective.

1.2 Scope and Intended Audience

In British Columbia, the requirements for post-wildfire natural hazards risk analysis are outlined in the B.C. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) policy manual (B.C. MFLNRO 2012). This policy provides a framework for the identification and assessment of risks to public safety, buildings, and infrastructure; identifies the roles and responsibilities of MFLNRO as the lead assessing agency; and outlines the role of Emergency Management BC (EMBC) in communicating the results of these assessments. It also identifies funding sources and defines the area within and beyond the wildfire to which the policy applies.

The policy states that “the MFLNRO document, *Standard Operating Procedure for Post-Wildfire Natural Hazards Risk Analysis*, will be used to guide MFLNRO’s identification, analysis and evaluation of the risk of post-wildfire natural hazards, and application of risk mitigation treatments, to ensure a systematic and consistent approach to risk management and communication.”

The policy clarifies that “a post-wildfire risk analysis is not intended to address (1) reforestation or enhancements to site productivity for the purpose of growing merchantable timber, (2) repairs to or replacements of range improvements, or (3) mitigation of damage to forests, range or aquatic habitats for those areas on Crown land affected by wildfire.”

This Land Management Handbook provides technical support for the policy by describing the minimum set of standard considerations that should be included in all assessments. The information will allow professionals to adapt their knowledge and experience to post-wildfire natural hazard risk analyses. This handbook will also inform government program managers, interested wildfire management staff, and staff in other agencies, such as EMBC, and in municipalities.

Although this handbook is for qualified registered professionals whose areas of practice are mandated under their respective enabling legislation, it is not intended to replace professional judgement or to preclude other assessments and analyses that are useful to any specific situation. The handbook does not intend to repeat the content of existing Practice Guidebooks and other guidelines or handbooks but rather describes related concepts and assessment procedures specific to wildfire. The current post-wildfire natural hazard risk analysis procedure will

evolve by incorporating the most current science and methods, and will be refined as post-fire experience increases throughout British Columbia.

1.3 Technical Terms and Definitions

Terms used by both operational fire management and post-wildfire assessment teams have developed over many years; consequently, the same terms can mean different things to a firefighter and a risk assessment professional. Wildfire management terms relate largely to wildfire potential (fire weather and fuel indices) and behaviour (fire spread, flaming, and heat output). Fire behaviour and heating affect the post-wildfire risk, but only in combination with the duration per unit area of any fire (DeBano et al. 1998; Parsons et al. 2010).

Many attempts have been made to clarify terms in the fire science literature to ensure consistency among both science and operational assessments (see DeBano et al. 1998; Lentile et al. 2006; Keeley 2009). Consistent use of terms will aid communication and help avoid confusion, both among risk assessment teams and between the risk assessment and fire management teams. It will also enable the experience and knowledge gained from U.S. BAER programs and U.S. Forest Service publications to be used in British Columbia and across Canada. To clarify meanings and enable reference to, and use of, recent U.S. BAER field guides (Parsons et al. 2010), the following commonly used terms are defined:

Burn (or fire) severity is a general term that most commonly describes the combined effects of both flaming and smouldering. The term meets a need to provide a description of how fire intensity has affected ecosystems (Keeley 2009) and other important attributes, and is inferred after the fact. Burn severity measures can be applied to measures of the atmosphere, ecosystem components (including flora, fauna, soil, and water), or human society (Canadian Interagency Forest Fire Centre 2002).

Burn severity, in broad terms and as applied in the British Columbia risk assessment procedure, refers to the effects of the fire on both the forest canopy and understorey (vegetation burn severity) and on the forest floor and soil (soil burn severity). It provides vital information for soil erosion, hydrologic, and landslide assessment.

Vegetation burn severity is a relative measure that describes the effect of a fire on vegetative ecosystem properties (Figure 2). It is often defined by



FIGURE 2 A mosaic of vegetation burn severity classes in the area burned by the 2009 Mount McLean Fire, Lillooet. Black areas mapped as high, brown areas (with needles) mapped as moderate, and green trees with underburn mapped as low. (Photo: T. Giles)

the degree of scorch, consumption, and mortality of vegetation, together with the projected or ultimate vegetative recovery (Parsons et al. 2010). Vegetation burn severity depends on fire intensity and the fire-resistant properties of the ecosystem. When mapped, it provides an overview of fire-related mortality across the burned landscape (Robichaud and Ashmun 2013). A simplified vegetation burn severity system of three classes (modified from Curran et al. 2006) is presented in Section 2.6.2.

Soil burn severity is a relative measure that describes the effect of a fire on ground surface characteristics and soil conditions that affect soil hydrologic function (Curran et al. 2006; Keeley 2009). The classification of post-fire soil condition is based on field assessments of the fire's alteration of soil and forest floor properties, including organic matter (litter, duff, and woody debris), and root loss, altered min-

eral soil colour and structure, char and ash depth, and reduced infiltration (Parsons et al. 2010). Determination and characteristics of the three classes of soil burn severity classes are presented in Section 2.6.2. Photo series of the important characteristics of each burn severity class are presented in Parsons et al. (2010). Examples of burn severity classes from British Columbia fires are shown in Figure 3.

The correlation between vegetation and soil burn severity ranges from strong to weak, depending on the fire. Different forest or vegetation types, such as dense forest, open forest, young plantations, and grassland may appear to have similar vegetation burn severities but have quite different soil burn severities. For example, soil burn severity may be high where smouldering ground fires existed, even though vegetation burn severity is moderate or low. In areas that burned rapidly with high fire intensity,



FIGURE 3 Ground views of burn severity classes: (a, b) low vegetation and soil burn severity; (c) moderate vegetation and soil burn severity; (d) high vegetation and moderate soil burn severity; and (e, f) high vegetation and soil burn severity. (Photos: a, c, d, e: G. Hope; b, f: P. Jordan)

vegetation burn severity is usually high, whereas soil burn severity may vary from low to high (see Section 5.4: 2009 Mount McLean Fire case study). The supply of fuel near the ground, pre-fire forest floor properties and moisture content, and vegetation condition strongly influence both vegetation and soil burn severity.

Fire intensity is a term that describes the energy release per unit time or area during the physical combustion of organic matter (Keeley 2009) during various phases of the fire. Fire intensity is a measure of real-time burning, and does not necessarily indicate the effects of the fire on vegetation and soil, or subsequent responses of those ecosystem components (Parsons et al. 2010).

Hazard and risk are two very distinct terms.

Hazard can be defined as those processes and situations, and actions or non-actions, that have the potential to damage, harm, or cause other adverse effects to human health, property, the environment, or other things of value (CSA 1997). In the context of natural processes that occur in forested environments, hazards include wildfire, soil erosion, floods, landslides, and snow avalanches. Hazard can be expressed in qualitative (relative) terms or in probabilistic (quantitative) terms. Table 1 presents an example of qualitative descriptions of hazard ratings.

TABLE 1 *Qualitative descriptions of hazard ratings (or the likelihood of occurrence of a natural hazard), adapted from Wise et al. (2004)*

Descriptor of hazard	Description
Very high	A specific post-wildfire hazardous event ^a is very likely or would occur soon after the wildfire.
High	A specific post-wildfire hazardous event is probable (likely) within the short term.
Moderate	A specific post-wildfire hazardous event is not likely but possible within the short term.
Low	A specific post-wildfire hazardous event is a remote possibility (unlikely) within the short term.
Very low	A specific post-wildfire hazardous event is a very remote possibility within the short term.

^a An event is most likely to occur under adverse weather conditions, such as high-intensity rainfall or rapid snowmelt.

Risk is a combination of the magnitude and probability of adverse effects. Risk has two components: the likelihood of something happening, and the

consequences if it does happen. Risk can be rated for a specific resource (specific or partial risk) or for all resources and values (total risk). Risk can be evaluated quantitatively using probabilities, or qualitatively using a risk matrix in which risk is simply defined as a product of hazard and consequence.

Risk analysis is the systematic use of information to identify hazards and estimate the probability and/or severity of injury or loss to people, property, the environment, or other things of value (CSA 1997; Wise et al. 2004).

A post-wildfire risk analysis usually describes, implicitly or explicitly, the change in hazard or risk due to the wildfire (the “incremental” hazard or risk), although the background or pre-existing risk is noted. Where post-wildfire incremental hazards are only “low,” the pre-existing hazard can mean that the overall hazard is higher than “low.” In such cases, the conclusions should state both the overall hazard and the incremental hazard (see Section 5.1: 2013 Perry Ridge Fire case study).

Risk management is a five-step process (CSA 1997; VanDine 2012):

1. identification of risk
2. analysis and estimation of risk
3. evaluation of risk tolerability
4. development of control or mitigation strategies
5. action on these strategies

The procedure described in this publication deals with only the first two steps.

Landslide is a general term for the “movement of a mass of rock, debris or earth down a slope” (Wise et al. 2004). Landslides include debris flows, debris floods, debris slides or slumps, and rockfall.

Debris flows are a very rapid to extremely rapid flow of saturated, non-plastic debris in a steep channel or gully (Hung et al. 2001). Most post-wildfire landslide events in British Columbia are debris flows. They are most likely to occur in small drainages with steep channel gradients and confined channels. Debris flows typically run out onto lower-gradient slopes, such as an alluvial fan, and deposit as sediment lobes or sheets. Debris flows can be very destructive, destroying many of the structures in their path (Figure 1).

Debris floods are a hybrid between a flood and a debris flow; several large debris flood incidents have occurred in channels that are of insufficient slope or confinement to carry debris flows. Although debris

floods are less destructive than debris flows and are not a landslide, they are included with landslides in this risk analysis procedure because they are often hard to distinguish in the field, and they both affect alluvial fans.

Debris slides or slumps in or below burned areas have been reported in British Columbia, although they are less common than debris flows. The mechanism for initiation is usually high groundwater levels due to increased water input from snowmelt; therefore, these events are sometimes called “infiltration-triggered” landslides (Cannon and Gartner 2005). Theoretically, large, inactive slump-earthflows or rockslides could be reactivated following wildfire,

although no instances have been reported in British Columbia.

Rockfall incidence commonly increases on steep slopes during and following wildfire because stabilizing vegetation is burned. An elevated rockfall hazard typically persists for several years following a wildfire. Rockfall in steep gullies that feed debris flow channels can be a source of increased post-wildfire debris flow hazard.

Snow avalanches are not a landslide process but are considered a geomorphic hazard because snow avalanche hazard often occurs in the same type of terrain that is subject to landslide hazards.

2 IDENTIFICATION OF POST-WILDFIRE HAZARDS AND RISK

2.1 Screening Wildfires for Risk

Because most wildfires in British Columbia do not result in significant post-wildfire risk, risk screening serves as a coarse filter to identify those wildfires that do pose a risk to public safety or infrastructure, and that will require a risk analysis.

Government natural hazard specialists screen reported wildfires using the Wildfire Management Branch database of fires, which is updated daily during the fire season. Fire Centre staff may also inform the natural hazards specialists when an active fire is of concern. Wildfires of concern are those that:

- exceed approximately 50 ha;
- have burned with moderate and/or high fire intensity;
- are located above or near populated areas or transportation corridors; or
- are within community watersheds.

Table 2 outlines the steps in the procedure after a wildfire has been identified as requiring a risk analysis.

2.2 Identifying Elements at Risk

Once a fire has been identified as being of concern, the first step in risk analysis is to identify the elements at risk that are downslope or downstream of the fire. Any object or asset may be at risk; however, the process described in this Land Management

Handbook and recognized in other government protocols applies to:

- residences or other occupied public or private buildings, usually located on alluvial fans;
- highways and other arterial roads, railways, utilities (e.g., pipelines, transmission lines);
- domestic water supplies, community water storage reservoirs, intakes, treatment plants, and other municipal infrastructure;
- recreational sites and campgrounds;
- agricultural land or industrial facilities; and
- other significant social or environmental values identified in District fire management plans or by the MFLNRO District Manager.

For interface fires, most of these elements at risk will have been identified during fire suppression, and measures such as evacuations or highway closures may be in place while the fire is active. After the fire is contained, the risk analysis team must determine which elements are at risk from post-wildfire hazards.

The potential post-wildfire hazards that are considered in this assessment procedure, and which may affect the elements at risk, include:

- erosion and sediment transport;
- floods;
- landslides; and
- snow avalanches.

TABLE 2 Overview of the post-wildfire natural hazards risk analysis procedure (adapted from Dobson Engineering 2007)

Step	Detail
1. Identify elements at risk	<ul style="list-style-type: none"> Determine the elements at risk. Appoint lead specialist; establish team, if required.
2. Conduct assessments	
A. Assemble background information	<ul style="list-style-type: none"> Assemble maps, including fire boundary, forest cover, soil, terrain and terrain stability, and air/ortho photos, as well as LIDAR images, where available. Map elements at risk. Delineate watershed boundaries. Compile past watershed and terrain assessments. Compile hydrometric data.
B. Map vegetation and soil burn severity	<ul style="list-style-type: none"> Conduct an overview flight to map vegetation burn severity and make observations of the burned area and downslope/downstream areas likely to be affected by the fire. Map burn severity (may be supplemented later by a Burned Area Reflectance Classification map). Complete on-site assessments of burned (and unburned) forest canopy and soil characteristics. Sample the range of burn severity and soil landscapes. Refine the burn severity map.
C. Identify hydrologic and geomorphic hazards	<ul style="list-style-type: none"> Assess conditions and changes in vegetation, soil erosion hazard, ground disturbance, drainage (roads and fireguards), and riparian and stream conditions. Conduct a field review of changes in landslide hazards and risks, including those on landslide-prone slopes, in gullies and channels, and on alluvial fans. Determine hydrologic and geomorphic hazards.
3. Complete a risk analysis	<ul style="list-style-type: none"> Determine qualitative partial risk: how the soil, hydrologic, and geomorphic hazards and risks have changed as a result of the fire.
4. Prepare a report	<ul style="list-style-type: none"> Prepare an initial (short form) report and communication of risk, followed by a detailed report, if warranted.
5. Detailed risk analysis and mitigation	<ul style="list-style-type: none"> Where necessary, conduct a detailed investigation of specific risks and risk mitigation treatments; may be done by other professionals.

2.3 Establishing Teams and Reporting Timelines

Where the need for a risk analysis is identified during screening, a lead specialist is appointed and the process begins. MFLNRO specialists most commonly conduct the risk analysis; however, external consultants are used if necessary during severe and very busy fire years.

The scope of the risk analysis and the size of the team depend on the types and number of elements at risk, the size and severity of the wildfire, and the complexity of the affected terrain, among other factors. For small, simple fires, the risk analysis may require only one person and limited fieldwork; often, the fieldwork components may be completed in one trip. In other cases, a team of specialists may be necessary. Such teams generally include professional

geoscientists, soil scientists, hydrologists, and/or engineers, and technical staff as necessary. For large or complex fires, multiple field trips by several specialists may be required to complete the assessment.

Initial fieldwork and mapping typically begins when the fire is substantially contained and the wild-fire incident command determines that it is safe for the team to work on the ground in the burned area. Some preliminary aerial reconnaissance may be conducted earlier. For large fires, it may be possible to divide the fire into high- and low-priority areas, and to conduct mapping and fieldwork only in the area of concern.

In some cases, it will be immediately obvious that a high risk exists (e.g., houses are on a debris flow fan below a severely burned slope). Such preliminary observations should be communicated to the

appropriate authorities (e.g., Fire Centre, incident command, EMBC) before work begins on the formal risk analysis.

A short post-wildfire natural hazard risk analysis preliminary report is required for all fires where the need for a risk analysis is identified (see Sections 5.1 and 5.2: 2013 Perry Ridge fire and 2010 Place Lake Complex Fire case studies), and preferably should be completed within 7 days of when it is safe to start work. The preliminary report confirms the elements at risk, identifies and characterizes the natural hazards, and estimates the partial risks; it may also contain maps.

Where high risks are identified, the preliminary report should be followed by a detailed risk analysis and report (see Sections 5.3, 5.4, and 5.5: 2009 Terrace Mountain, 2009 Mount McLean, and 2007 Springer Creek fire case studies). In such cases, the fires are generally upslope of communities, waterworks, or major transportation corridors; are large or complex; and/or may require expensive mitigation measures. A detailed risk analysis elaborates on the hazards and risks in the preliminary report, identifies any need for risk mitigation treatments, and provides detailed recommendations. Water quality concerns should also be addressed in detailed assessments for community watersheds.

All levels of risk analysis require some consideration of burn severity and post-wildfire soil, hydrologic, and slope stability conditions.

2.4 Assembling Background Information and Data

The first step in post-wildfire natural hazards risk analysis is to collate all available and relevant information for the burned and downstream area located above the elements at risk, including topographic maps, recent aerial photographs, and wildfire boundary and infrastructure maps. This information forms the background for field inspections and is necessary to describe watershed response to fire and to inform affected stakeholders and public agencies of potential risks.

2.4.1 Vegetation and soils

Characteristics of pre-burn vegetation, and natural disturbance and logging history, throughout the watershed(s) of interest should already be described. Forest cover and other geographic information is available at DataBC: www.data.gov.bc.ca/dbc/

[geographic/index.page?WT.svl=Topnav](http://www.data.gov.bc.ca/dbc/geographic/index.page?WT.svl=Topnav).

Soil, terrain, and bedrock types, and biogeoclimatic ecosystem classification (BEC) information and maps for the area of interest should be considered prior to mapping soil burn severity and assessing soil erosion hazard. An area mapped as one burn severity class may contain more than one soil burn severity class because of variations in: soil and forest floor type, depth, and moisture content; terrain types; vegetation cover; topography; and slope position, slope morphology and gradient, and aspect.

2.4.2 Hydrology

In the office, topographic maps, aerial photographs, wildfire boundary maps, and infrastructure maps should be assembled to identify and map streams, roads and other disturbances, fish reaches, water intakes, diversions and licences, private property, and public infrastructure and to delineate the boundaries of all watersheds upstream of the elements at risk. The locations of hydrometric monitoring stations in or near the area of concern should be identified, and the process of acquiring data should be initiated.

Watershed boundaries should be manually traced on the best available maps (usually 1:20 000 TRIM maps with 20-m contours) because automatically generated watershed boundaries are often unreliable. Watersheds, and the face units between them (intervening slopes without mapped streams), are delineated to the level of detail necessary to distinguish between different elements at risk and potential hazards. The point of lowest elevation in a watershed or sub-basin (point of interest) is determined by the presence of an element at risk, including features such as a fan apex, points of possible avulsion, undersized bridges and drainage structures, highway and railroad crossings, or water supply intakes. These features should be assessed well downstream of the burned area. Particular attention is paid to ambiguous drainage divides, especially where there are old roads or logging, because they are often the sites of drainage diversion into or out of the watershed.

Watershed size, elevation, aspect, relief, drainage density, lake area, alpine area, and forest cover, and the extent and distribution of logging and other disturbances, should be tabulated. These watershed attributes provide a general indication of the timing of slope- and watershed-scale streamflow response to rain and snowmelt. Burn extent by severity class,

both vegetation and soil, should be summarized for each watershed. Vegetation burn severity classes indicate where snow and rain reaching the slope, soil moisture, subsurface drainage, and surface runoff (Figure 4) are most likely to increase post-fire. Previous and current forest cover, if any, including species, stand age, density, and structure, within the burned area provides a general indication of the relative magnitude of potential increases in snow accumulation and melt rates and changes in rainfall interception.

The distribution of past disturbances and the burned area across different aspects and elevation ranges, as well as in relation to lakes, wetlands, and the elements at risk, should be described. This provides information on the potential for synchronization of runoff, and indicates if lakes or large wetlands might buffer such changes. The area within a watershed in which predominantly snowmelt-generated peak flows occur can be delineated by a lower elevation limit to the “snow zone,” which in the Southern Interior of British Columbia is often defined as the upper 60% of the total watershed area (H60) or some other elevation (e.g., H40), based on local knowledge. Forest disturbance in this portion of a watershed is assumed to increase the likelihood of earlier and possibly higher spring peak flows. Disturbance in the entire watershed area above the element at risk is assumed to contribute to elevated storm flows.

2.4.3 Geomorphology

In the office, topographic maps, aerial photographs, and terrain stability maps should be reviewed for clear indicators of landslide susceptibility. Where there was previous forestry activity on or above areas of potential post-wildfire landslide hazard, features such as active roads, crossings of debris flow channels, and points of potential drainage diversion should be identified.

Terrain maps can be used to locate unstable and potentially unstable terrain (Class V or IV from Detailed Terrain Stability Mapping or Class U or P from Reconnaissance Terrain Stability Mapping). Terrain maps also contain other useful information within the terrain classification identifier under geomorphic process, such as location and activity levels of debris flow channels, landslide runout zones, rockfall, or snow avalanches. If terrain stability maps are not available, the assessor must rely on 1:20,000 topographic maps to identify landslide-prone slopes or debris flow channels.

Longitudinal profiles can be quickly produced using the 1:20 000 topographic maps. The longitudinal profile plots the channel elevation versus distance and allows the channel to be divided into reaches. Channel gradients can be readily calculated for each reach. Key features such as roads, bridges, lakes, tributaries, or alluvial fans can also be plotted along channels of concern. Existing terrain stability mapping or aerial photographs can be used to identify al-

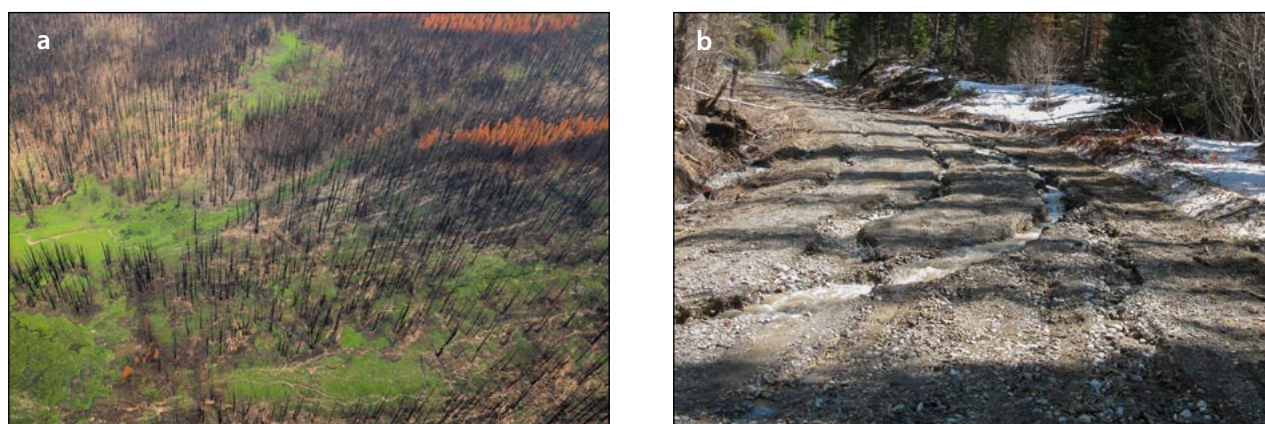


FIGURE 4 Surface flow of water produced (a) by overland flow from severely burned areas during summer rainstorm, and (b) by concentration and diversion of spring runoff flow by roads. Roads and trails can concentrate increased runoff from burned areas, from overland flow in summer or from increased spring snowmelt, leading to increased landslide hazard below. (Photos: a: R. Winkler; b: B. Chapman)

luvial fans that are potentially subject to debris flows or debris floods. Wilford et al. (2004) provide some criteria for identifying fans subject to debris flows.

A useful initial screening tool for stream channel and fan hazards is the Melton relief ratio (MRR), which is the ratio of watershed relief divided by the square root of watershed area. The MRR provides a first approximation of the hazards in a watershed; further investigation of the watershed, channel, and alluvial fan should be completed through air photograph interpretation and field investigation. Short, steep watersheds tend to have relatively high MRRs (> 0.6), and typically have streams that are subject to debris flows (Wilford et al. 2004; Millard et al. 2006). As watersheds increase in size, the overall gradient commonly decreases and the MRRs decrease; when the MRRs are in the range of 0.3–0.6, the streams are more likely to be debris-flood dominated (Wilford et al. 2004). Larger- and lower-gradient watersheds have MRRs < 0.3 and are most susceptible to flooding events.

2.5 Overview and Disturbed Area Assessments

Whenever possible, any field review should begin with an overview flight of the watersheds, above the elements at risk. The overview flight facilitates rapid identification of key areas that require ground inspection and provides an overview of burn severity and the hydrogeomorphic regime. Observations should focus on the area burned, including vegetation burn severity and burn pattern; roads, trails, and fireguards; slopes and channels within and downstream of the fire; watershed and sub-basin characteristics; natural hazards; areas affected by previous disturbance (natural and anthropogenic); and the elements at risk. The flight allows assessors to obtain a better feel for the watershed(s), channel characteristics, slope steepness, presence of pre-existing landslides, and relative geographic relationship between potential hazards and the elements at risk. Sites for burn severity assessment and further field investigation can also be determined.

On the ground, roads and fireguards within the area burned and downslope and downstream of the fire should be assessed if significant changes in peak flows or sediment loads are likely. Particular attention should be paid to areas where roads or trails and fireguards divert subsurface water to the surface, or concentrate water along road and guard surfaces and in ditches that are connected to streams (Figure 4b). After

wildfire, road drainage systems may be overwhelmed by increased runoff. Undersized and damaged ditches, culverts, and bridges should be noted and/or mapped.

2.6 Burn Severity Assessment

It is essential to assess burn severity, or the impact of a wildfire on vegetation and soils, before hazards and risks can be fully determined.

Burn severity assessment is a four-step process:

1. preparation of a preliminary burn severity map
2. development of preliminary vegetation and soil burn severity strata
3. field assessment of vegetation and soil conditions
4. preparation of the final burn severity and vegetation and soil burn severity maps

Mapping should be completed by professionals experienced in mapping natural features such as vegetation, soils, ecosystems, and terrain. In British Columbia, standards, manuals, and guidelines for mapping ecosystems, terrain, and soils are available from the B.C. Ministry of Environment's Species and Ecosystems Information Portal: www.env.gov.bc.ca/wld/ecobranh_info_portal/index.html.

2.6.1 Preparing the preliminary burn severity map

Preparing a burn severity map is an essential first step in conducting risk analysis for most fires, especially when making hydrologic and slope stability assessments. A burn severity map allows the integration of hazards and cumulative effects over the area burned as well as larger areas downslope or downstream of the burned area and upstream of an element at risk.

Burn severity maps can be produced by hand, based on aerial observations (termed visually derived burn severity maps) or remotely sensed satellite images (termed satellite-derived burn severity maps). Hand-drawn maps are suitable for low-risk fires, and can also be suitable for large or high-risk fire areas until a more accurate and detailed Burned Area Reflectance Classification (BARC) product can be generated from satellite imagery. The BARC map is usually easier to prepare, and the final product is more precise and accurate than a hand-drawn map (Parsons et al. 2010); however, its production may be delayed until a useable post-fire LANDSAT image is acquired.

Aerial observation or remote sensing can be used only to produce maps of vegetation burn severity; field or on-the-ground observations are required to modify these maps and to produce a soil burn severity map (Safford et al. 2007).

Visually derived burn severity mapping For small fires, burn severity can sometimes be mapped directly on a paper map during the overview flight, although it is usually preferable to systematically take oblique aerial photos from a helicopter or airplane and then sketch burn severity polygons onto a topographic or forest cover map or onto an orthophoto. For a very large fire, the entire area of the fire need not be mapped if only a small part of the fire is of concern for assessing risks. Information obtained from aerial observations and photography can be supplemented with any information available from wildfire management teams.

Experienced assessment team members may estimate vegetation and preliminary soil burn severity from the air, but these estimations must be ground-checked. Parsons et al. (2010) provide examples of canopy condition that illustrate potential soil burn severity class, as estimated from the air or from the ground, for different forest types. Figures 2, 3, and 5 show examples of soil and vegetation burn severity in British Columbia.

Satellite-derived burn severity mapping A BARC is a digital mapping product derived from pre- and post-wildfire satellite imagery that is used to classify post-fire vegetation and ground condition. BARC mapping based on LANDSAT imagery is routinely used by the U.S. Forest Service and other agencies, and more recently by MFLNRO, to prepare burn severity maps. The preparation of a BARC map requires expertise in ArcGIS. Risk analysis team members should contact geospatial services departments within MFLNRO for assistance in obtaining uncalibrated BARC maps for British Columbia.

The BARC is based on the different reflectance of green vegetation and freshly burned areas in two spectral bands: the near infrared and the mid-infrared (commonly known as the shortwave infrared). The methods for preparing a BARC are well documented (e.g., Brewer et al. 2005; Key and Benson 2006).

An initial BARC displays burn severity classes of low, moderate, and high, plus unburned. These initial classes may be a reasonably good fit to field observations of vegetation and/or soil burn severity

for some fires in uniformly dense forest. However, for most fires, the classification needs to be field validated, and if necessary, altered to better represent conditions on the ground.

The BARC can be validated directly to produce a map of soil burn severity (see Appendix D in Parsons et al. 2010) or it may be calibrated in a two-step process to first produce a vegetation burn severity map, and then a soil burn severity map (see Section 5.3: 2009 Terrace Mountain Fire case study). Either procedure is acceptable.

2.6.2 Assessing burn severity in the field

The preliminary map will most likely have three or four severity classes (mapping units). In the field, areas initially delineated as a single burn severity class may be found to include several classes because of variations in soil and forest floor type, depth, and moisture content; terrain types; vegetation cover; forest floor cover; topography; and slope position, slope morphology and gradient, and aspect. All of these factors may influence the amount and duration of soil heating and the occurrence of soil water repellency, either directly or indirectly, by their effect on soil moisture at the time of the fire. For example, fires that occur when the forest floor and soil are still moist but when the elevated fuels and vegetation are dry may result in high vegetation burn severity but low soil burn severity.

When checking burn severity on the ground, the assessor is both validating (verifying and/or refining) the preliminary map and BARC classification and characterizing the burn severity classes. There may be a natural tendency for field crews to focus their attention on severely burned areas; this is justified for risk analysis and treatment prescription purposes. However, areas of low and moderate burn severity should not be neglected when collecting field data. At a minimum, three field test sites should be selected within each preliminary stratum (burn severity/site or soil factor combination) for each of the preliminary burn severity classes. The number of sample plots will increase with greater variation in observed soil burn characteristics. Highest priority should be placed on conducting field checks in areas with known hazards and/or above elements at risk, and then extrapolating to areas considered to be less hazardous. Parsons et al. (2010) state it simply as “Focus the majority of the field time in the black [high]” because severe erosion and runoff will most likely occur in these areas.

Field sites should also include sample points in unburned forest within or near the burn perimeter. These unburned locations will provide information on forest floor, water repellency, and fuel characteristics, which can be compared with burned soil observations, and they will provide map calibration points. Map validation sites can also be used as burn severity characterization plots, which will increase efficiency and reduce the number of site visits required.

If possible, validation points should be located near the centre of an area that is at least 1 ha and has uniform burn severity, pre-fire forest cover, and topography. In particular, such points should avoid locations within about 50–100 m of edge features, such as roads, fireguards, cutblocks, streams, and rock outcrops.

If parts of the fire are inaccessible, or if there is insufficient time to collect field calibration data, additional validation points may be created using photos taken from the air. Representative points in each burn severity class can be identified on the post-fire photos and located on a pre-fire orthophoto to obtain the co-ordinates. These pseudo-points can be used to verify and refine the BARC map, but they provide only limited information on soil burn severity.

Areas of recent or old logging within a burned area can present challenges for mapping burn severity. Therefore, recent cutblocks should be identified, field checked, and mapped as a separate category; vegetation burn severity in clearcuts is often undefined on the preliminary map because there is no forest canopy vegetation, but it is refined in the field based on any remaining green trees or other vegetation, and/or condition of standing dead trees (Table

3). Usually, soil burn severity is low to moderate in clearcuts or young plantations, but it can be high if logging was in progress at the time of the fire and there was a large amount of felled timber and debris on the ground. Where established plantations have burned, they may appear to have a burn severity class similar to that of high burn severity mature forest. However, soil burn severity in established plantations may be relatively low compared with burned forest because of a lack of dry or large fuel; therefore, field checking is essential. Areas of grassland or deciduous brush, open forests with grass understorey, and clearcuts with grass cover may need to be classified separately when preparing the validated BARC map. Other non-forest land types such as bare rock or wetlands should also be classified separately.

The detailed field form in Appendix 1 lists all the soil, site, and burn severity information to collect while conducting assessments. Site characteristics, including terrain type, BEC characteristics, aspect, slope, pre-fire forest cover, and pre-fire disturbance, should be collected for each stratum.

Vegetation Burn Severity Forest cover and understorey attributes affect interception, snowmelt, surface runoff, and erosion immediately post-fire and over longer timeframes.

Pre-fire conditions should be contrasted with those post-fire. The condition of conifers and broad-leaved species in both the overstorey and understorey should be clearly described in terms of pre- and post-burn canopy closure and condition (green, brown or red, black, none), density and extent of green vegetation, and tree stem/bark condition

TABLE 3 *Vegetation burn severity for coniferous forest, and its relationship to Burned Area Reflectance Classification (BARC) and soil burn severity classes*

Vegetation burn severity class	Definition	BARC class	Typical soil burn severity class
High (black)	Canopy trees blackened (charred) and dead, needles consumed, understorey burned	High	H or M
Moderate (brown or red)	Trees burned and dead, scorched needles remain on canopy trees, understorey burned and blackened	Moderate	M or H, can be L
Low (green)	Canopy unburned, trunks partially burned, understorey lightly or patchily burned	Low	L, can be M or H
Unburned	Vegetation in natural unburned state	Unburned	

(Figure 5). Canopy and tree stem condition may change over a number of years after a fire as burned trees lose remaining canopy material, blackened bark sheds, trees topple, and partially damaged trees recover or die.

The short field form in Appendix 1 includes a summary checklist, based on criteria given in Table 3, for classifying vegetation burn severity.

Vegetation burn severity, as used in the British Columbia procedure, largely reflects the immediate post-fire condition of the forest canopy and understorey. For risk analysis purposes, vegetation burn severity assessment is of primary importance in evaluating post-fire hydrologic processes related to the interception of precipitation (rain and snow) and snowmelt. It is also useful if evaluating longer time effects, as any indication of the severity of the fire on the vegetation and its ability to recover helps in predicting longer-term effects on watershed response and in determining possible risk mitigation efforts (Safford et al. 2007).

Soil Burn Severity Wildfire effects on soil properties that are important in controlling surface runoff and erosion can be broadly summarized as:

- causing the loss of protective ground cover, mainly the forest floor;
- causing the formation of water repellent soil conditions; and
- creating burned mineral soils with reduced cohesion and higher erodibility.

More detailed discussion can be found in Neary et al. (2005), Curran et al. (2006), and Shakesby and Doerr (2006).

Post-wildfire soil assessments should focus on specific properties that affect soil hydrologic function: forest floor depth and distribution, woody debris presence and burn condition, ash and mineral soil colour, mineral soil structure, live roots, and water repellency (Appendix 1). The level of detail should enable the assessor to provide a reasonable estimate



FIGURE 5 Low (a) and high (b) vegetation burn severity in the area burned by the 2009 Mount McLean Fire. As vegetation burn severity increases, so will post-fire hydrologic response. (Photos: R. Winkler)

of soil erodibility and soil hydrologic characteristics across the burned area for use in subsequent hazard assessments. Any evidence of recent post-fire overland flow or soil erosion should be noted.

Instructions for assessing specific properties that affect soil hydrologic function are as follows:

1. **Forest floor:** Determine the average depth of the remaining forest floor layer and a comparable unburned forest floor, if possible. Record the presence of any live roots and the approximate percentage cover of the remaining forest floor. Also determine the condition of remaining large woody debris (unburned, charred, consumed) and estimate its percentage cover. Record variations in the forest floor type if the types are sufficiently different that moisture storage capacity and erosion protection will vary markedly for a similar depth. If needles scorched during the fire have fallen to the ground, estimate the percentage of ground covered by them.
2. **Mineral soil:** Assess and record texture and coarse fragment content of the surface soil layers. Assess (visually/by touch) changes in soil structure compared to unburned areas; such changes are often associated with a change in the colour or cohesion of the mineral soil (e.g., localized red colours or reduced aggregate stability usually indicate high soil burn severity). Record the depth of any layer that has structural loss. This layer will often be wettable, although not all wettable layers have altered soil structure. Note ash colour and depth, and the percentage of exposed mineral soil (Figure 6a). Record the depth to live roots in the mineral soil (Figure 6c); presence or absence of fibrous roots and fungal mycelia in the soil may also be noted, as these provide additional information on soil erodibility or depth of heating.
3. **Water repellency:** To assess water repellency, use a short-duration water drop penetration test (WDPT) (Letey 1969) (Figures 6a and b) and/or a mini-disk infiltrometer (MDI) test (Robichaud et al. 2008). Both tests detect water repellent conditions; the MDI will also indicate the relative infiltration capacity of the soil. The WDPT involves determining the length of time for a drop of water applied to a mineral soil layer to penetrate the surface of that layer (i.e., rate of infiltration into the mineral soil surface). Because these tests determine different aspects of repellency and infiltration, it is best to use both.

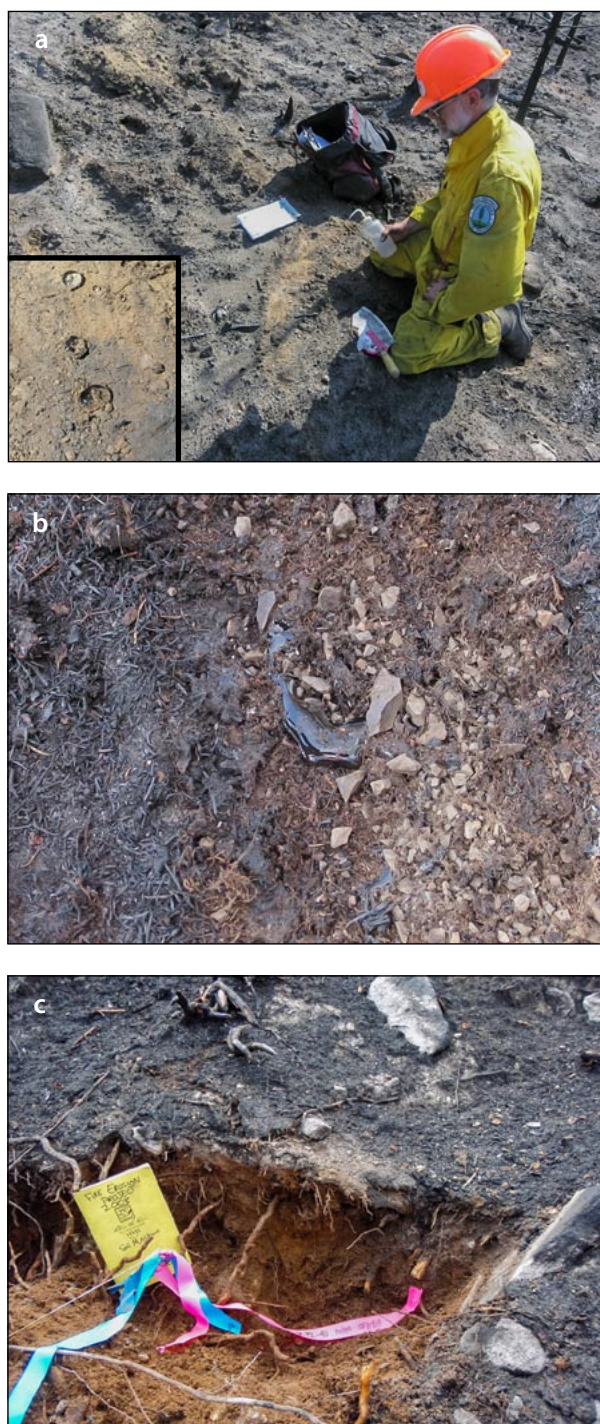


FIGURE 6 Components of assessing soil burn severity: (a, b) testing for water repellency, and (c) measuring depth to live roots. (Photos: a: P. Jordan; b: T. Giles; c: A. Covert)

Use the WDPT to determine if water repellency is present and the location of the repellent layer—at the surface or within the top 5–7 cm of mineral soil. The occurrence of wettable layers (water drops infiltrate the layer within 3–5 seconds) should also be recorded. Moisture content of the soil should be noted, as this will influence water repellency. This stage of the investigation occurs very rapidly.

If water repellency is found, conduct a more detailed assessment of the water repellent layer as follows:

1. Determine the horizontal extent of the water repellent layer by excavating or removing the forest floor or ash from a line at least 50 cm in length (one line per plot) within the repellent layer. Apply water drops to the mineral soil along the length of the line. Drops remaining longer than 40 seconds indicate strong water repellent conditions. Estimate the proportion of the line that is water repellent; this provides an estimate of the extent of water repellency.
2. Separately assess infiltration into the mineral soil surface using the MDI at three to five points per test site. Carefully remove the remaining forest floor or ash and create a level spot before determining infiltration. The suction rate on the infiltrometer should be set near to 1 cm. Record the time to the appearance of the first bubble, and the volume that infiltrates in 1 minute. See Robichaud et al. (2008) and Parsons et al. (2010) for more details on measuring infiltration.

Experience in British Columbia supports Parsons et al.'s (2010) suggestion that three classes of water repellency be used: strong, weak, and none (Table 4).

TABLE 4 *Relationship of water repellency classes to the water drop penetration test (WDPT) and mini-disk infiltrometer (MDI) test (from Parsons et al. 2010)*

Class	WDPT test (s)	MDI test (ml/min)
Strong	>40	0–<3
Weak	>10–40	3–8
None	0–10	>8

Soil burn severity class: Estimate the soil burn severity class using the detailed descriptions and photo series of the important characteristics of each class provided in Parsons et al. (2010) and Table 5. All fac-

tors should be considered together when classifying soil burn severity. Not all possible indicators must be present, but generally, two or more factors of high severity dominating an area may justify a classification of high soil burn severity for that polygon (Parsons et al. 2010). Also note any inclusions of other burn severity classes within the mapped polygon, and include a percentage estimate, if possible.

2.6.3 Preparing the final burn severity map

As with all resource inventory or mapping, the needs of the end-users should dictate the complexity of the map. Experience in British Columbia and the United States suggests that three burn severity classes (plus an unburned class) are sufficient for predicting erosion and surface runoff hazards, especially considering time and resource constraints for most of the mapping.

The characteristics of the burn severity classes may vary with the fire and watershed, but each class will be characterized by four properties: vegetation condition and coverage; duff (FH layers) depth and coverage; exposed and altered mineral soils; and water repellent soil conditions. Summary data should also include the percentage of each class within the burned area and in each catchment, when required.

During the field mapping, and at the final map production stage, decisions will need to be made about minimum polygon size, map scale, and map legend detail (see British Columbia mapping standards for terrain or soils for a full discussion). During field mapping, field inspection density will vary according to access, time, and resource constraints.

Consideration also needs to be given to what characteristics to include in the map. Pure burn severity polygons will generally be unlikely because of variations in terrain, soil, vegetation, and fire behaviour. Map unit purity should be addressed and described (DeBano et al. 1998).

The calibrated soil burn severity map provides a basis for predicting soil erosion and assessing hydrologic and geomorphology hazards. The map should be understood by all professionals and carefully validated in the field. The map is considered essential for conducting risk analysis in small, steep watersheds with possible debris flow hazards and downstream elements at risk. Hazards are determined by using the burn severity map together with an assessment of other properties such as terrain, climate, stream characteristics, and slope stability.

TABLE 5 *Soil burn severity classification based on post-fire appearance and forest floor and soil properties (adapted from Curran et al. 2006; based on DeBano et al. 1998 and Parsons et al. 2010)*

Soil and forest floor factors	Soil burn severity		
	High	Moderate	Low
Litter	Consumed	Mostly consumed	Scorched, charred, patchily consumed
Duff (FH layers)	Consumed in most locations	Deep char, may be consumed	Intact, surface char
Woody debris – small	Consumed	Partly–completely consumed	Partly consumed, charred
Woody debris – logs	Many consumed, others deeply charred	Charred	Charred
Ash colour (if still present)	Fine, white or grey	Greyish or blackened	Black
Mineral soil exposure (may still be covered with loose ash or charcoal)	>40%	<40%	Little
Mineral soil	Altered structure, porosity, etc.; often grey or reddish around burned large fuel; often strongly water repellent	Unchanged; water repellency is slight or patchy	Unchanged
Depth to live roots or rhizomes (in mineral soil)	>5 mm	0–5 mm	0 mm

2.7 Soil Erosion Hazards

Soil erosion and surface runoff hazards depend on soil burn severity and other factors that affect soil erodibility (B.C. Ministry of Forests 1999a; Curran et al. 2006). Important factors to consider when evaluating soil erosion hazard after wildfires include:

- Slope and surface topography.
- Soil burn severity class mapped distribution. Consider the location of classes downslope of high burn severity areas, and the locations of high burn severity areas relative to streams and terrain features. For example, only a small portion of a watershed needs to have high soil burn severity and strong water repellent conditions for overland flow and flooding to occur, especially if it is located in a catchment's headwater area; the debris flow off the Kuskonook fire (Figure 1) resulted from such a situation. Accelerated surface runoff and soil erosion from high soil burn severity areas may be ameliorated by unburned and green areas downslope of the burned areas, and by gentle slopes around creeks. Lower soil burn severity areas on gentle terrain may trap sediment and reduce surface runoff before it reaches any creeks.
- Surface cover and condition. Surface soils with high coarse fragment content or abundant downed wood may limit rill erosion and promote infiltration, thus reducing the likelihood of extensive overland flow. Soil erosion hazards are also mitigated, in part, by litterfall after the fire. Experience from Interior British Columbia (see Section 4.5.3) and research from the United States (Pannkuk and Robichaud 2003) has shown that under areas of brown trees, needlefall provides mulch that limits rainfall impact and subsequent surface soil erosion. In low soil burn severity areas, needlefall, an intact forest floor, and the green tree canopy generally provide protection from both overland flow and soil erosion. Conversely, extremely stony soils may increase overland flow if the forest floor's protective covering has been removed by fire.
- Season of the year. Soil erosion hazards are greatest with dry soil conditions, low vegetation cover, and high rainfall intensities (i.e., rainstorms in summer/early fall with dry antecedent soil moisture). Water repellency tends to decrease significantly when soils have prolonged contact with moisture, including wet snow and meltwater in spring; consequently, soil hazards are reduced after prolonged rainfall and spring snowmelt.

Water repellent conditions may reoccur in subsequent dry seasons for several years (Curran et al. 2006).

- Soil water repellency. The presence of strongly water repellent soils increases the probability of overland flow in high-intensity rainstorms. However, the probability of overland flow also increases significantly in areas of bare mineral soil (or high burn severity) without water repellency because the loss of forest floor reduces moisture storage capacity and surface roughness, and increases pore sealing by ash and eroded fine soil. Disaggregation of the mineral soil also greatly increases the susceptibility of the surface soil to erosion (Doerr et al. 2009). In the western United States, many post-wildfire flood and erosion events have occurred in areas of high soil burn severity without strong water repellency (Cannon and Gartner 2005).

High soil erosion hazards indicate areas where factors that affect hydrologic response, such as infiltration rate and erodibility, are most likely to be of concern (Robichaud and Ashmun 2013). In summary, assessment of the soil erosion and surface runoff hazards provides the basis for estimating runoff, flooding, erosion, and sedimentation hazards in the hydrologic assessment, and potential landslide hazard in the geomorphic assessment.

2.8 Hydrologic Assessment

The objectives of the post-wildfire hydrologic assessment are to determine:

- if the fire and fire control measures have sufficiently modified vegetation, soil properties, flow networks, and stream channels to affect hydrologic response;
- if these changes are likely to increase sedimentation, landslides, and flooding downslope and downstream of the burned area; and
- if these changes increase threats to the elements at risk.

Fire effects on hydrologic processes vary depending on burn intensity, extent, and location in a watershed but may include reduced interception losses, decreased infiltration rates, increased soil moisture, increased surface erosion, and loss of riparian protection. In turn, streamflow volume and timing,

water quality, and aquatic habitat may be affected within and downstream of the burned area. Numerous publications provide general reviews of the effects of wildfire and forest cover loss on hydrologic processes, including DeBano et al. (1998), Neary et al. (2005), Pike et al. (2010), and Winkler et al. (2010a, b). Assessing the effects of post-fire hydrologic response involves understanding the interrelationships between, and feedback mechanisms among, hydrologic processes (precipitation, interception, evaporation, infiltration, and runoff) and soil/sediment erosion and transport (Moody et al. 2013). This procedure is similar to standard watershed assessments that involve office and field assessments, data synthesis, and risk analysis (B.C. Ministry of Forests 2001; Wilford et al. 2009; Pike and Wilford 2013) but focusses on the burned area, linkages between hydrologic response and soil erosion, landslides and snow avalanches, and downstream cumulative effects such as flooding.

2.8.1 Hydrometric data

Once the fire boundary and downstream elements at risk have been identified, watersheds affected by the fire have been delineated, and watershed characteristics have been described, all available hydrometric data should be collated. These data include precipitation (both rain and snow) and streamflow. Hydrometric data may or may not be available for the area under assessment.

Storm type and precipitation form, depth, intensity, duration, and recurrence interval all affect hillslope and watershed response to rain and snow. Climate-related data can be obtained from the B.C. Ministry of Environment Climate Related Monitoring Program website (www.env.gov.bc.ca/epd/wamr/crmp.htm) and the Pacific Climate Impacts Consortium (PCIC) data portal (including PRISM data, British Columbia station data, and instructions for retrieving and downloading data): www.pacificclimate.org/data.

Where available, these data should be summarized at temporal intervals and spatial scales that correlate best with post-wildfire response. For example, soil erosion rates best correlate with 10-minute rainfall intensities, debris-flow timing with 15-minute intensities, and peak storm flows with 30-minute rainfall intensities (Moody et al. 2013). It also is noteworthy that calculating averages may obscure valuable information such as lag-times between storms and runoff. Care should be taken

to consider individual records, extreme values, and the data distribution of any hydrometric parameter being considered. In addition to antecedent conditions, infiltration, drainage network pattern, and topographic storage, runoff response to rainfall is also linked to spatial scale. Generally, as spatial scale increases, threshold rainfall intensity for runoff generation increases significantly. The importance and consequences of decisions made about which rainfall metrics to use is outlined in Moody et al. (2013).

Streamflow data are available from the Water Survey of Canada: www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=4EED50F1-1. Additional data collected by MLFRNO as part of short-term monitoring projects or at long-term research installations may also be available and can be requested by contacting the local regional MFLNRO office.

A detailed summary of data sources, watershed descriptors, and approaches to data compilation that are useful in characterizing both precipitation and hydrologic regime is provided in Pike and Wilford (2013). Where hydrometric data are unavailable, data from nearby stations may be extrapolated, provided caveats are considered, or the hydrologic regime may be described qualitatively. Care should be taken whenever data are extrapolated to ungauged areas.

2.8.2 Field review

On the ground, particular attention should be paid to vegetation, soil, road and fireguard (Figure 4), riparian, and stream conditions (Figure 7).

The condition of riparian areas and wetlands within the burned area should be clearly described. Variables useful for describing riparian health are included in B.C. Ministry of Forests (1996) and Tripp et al. (2007), and are summarized in Nordin (2008). Also, burn severity; surviving vegetation type, density, and distribution; and disturbance related to firefighting within the riparian zone should be described. In addition, increased access to both ephemeral and perennial streams by wildlife, cattle, and humans should be noted, and barriers or points of access should be mapped. The potential effect of riparian areas and wetlands on runoff attenuation, sedimentation, channel stability, access to water, and consequently water quality should also be considered.

Channel condition should be assessed at key locations, such as culverts, bridges, and confined or unconfined segments of channel, within the burn as well as downslope and downstream. Water piracy across

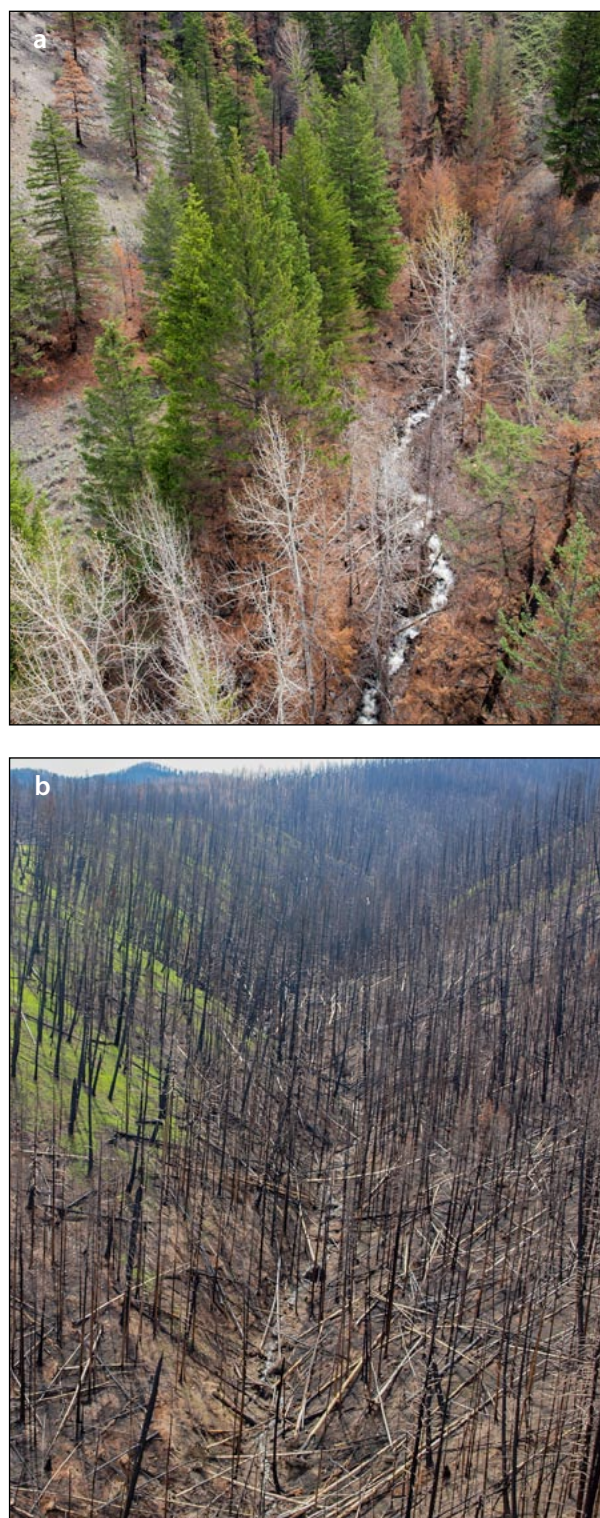


FIGURE 7 (a) Low and (b) high riparian vegetation burn severity. Surviving vegetation and retained surface cover affect channel stability, sedimentation, accessibility, and consequently, water quality and aquatic habitat. (Photos: R. Winkler)

slopes and damage to water conveyance structures should be described and their locations mapped.

2.8.3 Hydrologic hazards

Hydrologic response to wildfire depends on fire severity and extent, hillslope and watershed characteristics (including forest cover, soil properties, and hydrologic regime), time since the fire, non-fire-related disturbance, and weather. Experience in southern British Columbia indicates that the main immediate concern during or immediately after wildfires is the occurrence of very large storm flows resulting from high-intensity late summer or fall rainfall onto bare soil (Jordan and Covert 2009). The sequence and timing of rainfall, and the contributing area, soil hydraulic properties (such as water repellency), connectivity of flow paths (via bare ground and water repellent patches), presence of topographic depressions (including burned out stump and root holes), and surface roughness (including wood, litter, and ash) influence the magnitude of response (Moody et al. 2013). Reduced infiltration on severely burned slopes and other disturbed soil areas increases the likelihood that runoff during rainstorms and snowmelt will be concentrated along slopes and roads and ditches, and consequently, in streams, which may increase downstream storm flow peaks and cause geomorphic damage. Intense rainfall on high severity burn sites can cause storm flow to increase up to one or two orders of magnitude (Scott 1993; Neary et al. 2005).

In snow-dominated watersheds, forest cover loss due to wildfire generally results in increased snow accumulation (5–70%), earlier onset of snowmelt, increased snowmelt rates (30 to >100%), increased spring runoff and soil moisture, and spring runoff that potentially leads to increased water yield, high flows, and late-season flows (Burles and Boon 2011; Semmens and Ramage 2012; Gleason et al. 2013; Winkler et al. 2014). Depending on vegetation burn severity, significant changes in snow processes may not occur until several years post-wildfire when any remaining fine canopy material (red needles, twigs, fine branches) has been lost. The magnitude of snow response post-fire depends not only on the weather and forest structure, including stem and canopy density, tree height, tree species, and forest health, but also on geographic location, elevation, and aspect.

In general, changes in streamflow volume and pattern are greater the more extensive the burn and the higher the soil and vegetation burn severity;

however, these changes are also highly dependent on the weather in the years immediately following the fire. Research in the Fishtrap Creek watershed north of Kamloops, B.C. quantified streamflow response following a fire that burned more than 62% of the total area of this snow-dominated watershed; the timing of the annual peak flow advanced approximately 2 weeks, although the magnitude of flow did not change significantly. This minimal response was thought to be due to low winter precipitation and summer rainfall intensities during the first year post-fire, rapid vegetation recovery in subsequent years, and decoupling of hillslopes from channels. Channel migration and increased bank erosion 3–5 years post-fire were the most significant changes observed (Owens et al. 2013). In contrast, peak flows after severe wildfires in the western United States were 1.4 to over 870 times those measured pre-fire, depending on the burn severity, vegetation, soil, geology, slope, and climate (Neary et al. 2005). Research on streamflow response to clearcut logging also suggests what changes can be expected post-fire. Green and Alila (2012) found that peak flows increased 11–35% and timing of peak flows advanced after 33–40% of the watersheds was clearcut. The authors also found that the frequency of high flow events of all magnitudes increased. Winkler et al. (2014) found that at 50% forest cover loss, total water yield in spring increased significantly, while early summer flows may decrease as a result of earlier snowmelt. Response is generally greater in smaller watersheds due to short times of runoff concentration and synchronization of runoff. In large watersheds, changes in flow may be minimized by desynchronization of runoff across diverse aspects, elevations, and slope types, particularly where lakes or wetlands are present. Changes in streamflow magnitude and frequency of high flow events are likely larger after fire than after clearcut logging, depending on burn severity and extent, because of loss of vegetation and forest floor, changes in soil surface properties, and increased antecedent moisture.

Water chemistry, physical quality, and temperature may change following wildfire, depending on burn severity, buffering capacity of soils, proportion of watershed burned, season in which the fire occurred, rate of vegetation regrowth, and streamflow regime (Pike et al. 2010; Jordan 2012). Increases in suspended sediment, bank erosion, and channel migration are often measurable at least 5 years post-fire (Owens et al. 2013). Stream temperatures will likely

increase where riparian cover has been lost (Leach and Moore 2010; MacDonald et al. 2014). Nitrogen and phosphorous concentrations in streams will most likely be elevated, at least during the first few large storm events and during snowmelt the season following the fire (Gluns and Toews 1989; Bladon et al. 2008; Smith et al. 2011).

The duration of hydrologic change after wildfire depends largely on the extent of damage to soil, slopes, and stream channels during both the fire and subsequent storms or snowmelt, and on rates of revegetation. Regrowth of forest vegetation, both overstorey and understorey, reduces snow accumulation, delays the onset of snowmelt, reduces ablation rates, and buffers streamflow response to storms, and thus moderates post-fire increases in spring peak and storm flows. Changes in flow can persist for at least 20 years, until the structure of the new forest approaches that of the pre-fire forest. Changes in water quality may persist until ground cover becomes established and animal access to channels becomes difficult.

Changes in hillslope drainage volumes and pattern, increased soil erosion and sediment loading in streams, and destabilization of channel beds and banks should be considered during the geomorphic assessment because they may trigger larger geomorphic events both within and downslope or downstream of the burned area.

2.9 Geomorphic Assessment

2.9.1 Field assessment

Where there are elements at risk from landslides, the geomorphic assessment should follow a similar approach as terrain stability assessments for forest development. Terrain stability mapping, as well as any other landslide hazard or alluvial fan mapping, should be reviewed as part of the risk analysis procedure. Standards for terrain stability assessment are given in B.C. Ministry of Forests (1999b) and Association of Professional Engineers and Geoscientists of British Columbia (2010).

The geomorphic assessment uses everything learned from the vegetation burn severity mapping, soil burn severity testing, and hydrological assessment to determine the potential for landslide initiation. Slope position, gradient, and roughness; surficial material genesis; soil moisture and texture; and geomorphic processes are taken into account. Key to this is an understanding of what

properties have changed as a result of the wildfire.

In watersheds that are susceptible to debris flows, channel slope and confinement dictate the ability of a stream to initiate, transport, and deposit the debris flow. In British Columbia, debris flows after a wildfire are most commonly triggered by high peak flow in channels (Jordan 2015), but they may also be triggered by open-slope landslides (Figure 8) entering a confined channel or by progressive bulking of sediment eroded from the burned area. The channel slope required for within-channel initiation of debris flows is generally $> 40\%$, while lower slope angles may generate debris floods with sufficiently high discharge. Transport in a channel continues if the channel remains confined and the gradient is greater than approximately 15% for coarse-textured debris. If the gradient decreases or the channel becomes unconfined, the debris flow loses the ability to flow and begins to deposit on an alluvial fan. Fans on most perennial streams generally have gradients $< 15\%$, and their stream channels are commonly unconfined, which allows lateral migration of the channel and broadcasting of alluvial sediment across the fan surface. The change at approximately 15% gradient is typical of coarse-textured debris flows observed in British Columbia that originate from terrain underlain by competent rocks such as granite or gneiss. Debris flows often occur on gentler gradients if the source materials contain a substantial amount of clay or finely fractured or decomposed bedrock. Such source materials are common in Quaternary and Tertiary volcanic rocks and in the weak sedimentary rocks of the Rocky Mountains.



FIGURE 8 Debris slide initiated in an area severely burned by the 2007 Springer Creek Fire. (Photo: P. Jordan)

2.9.2 Geomorphic hazards

Once all the office data have been compiled and the field investigation has been completed, the geomorphic assessor must determine the overall potential landslide hazards in or below burned areas and above elements at risk.

Soil burn severity affects surface soil erosion and surface runoff, and subsequent landslide hazard. Therefore, post-wildfire landslide hazard increases approximately in proportion to soil burn severity. On the British Columbia coast, loss of root strength may also increase the likelihood of landslides. As with hydrologic hazard, high-intensity late summer or fall rainfall on high soil burn severity areas on susceptible terrain is of greatest concern regarding landslide initiation. The distribution of high-severity soil burn areas in the catchment is also important—severely burned areas at upper elevations can cause the greatest hazard.

Post-wildfire debris flows usually occur in gullies and channels that are subject to such hazards under pre-wildfire conditions, but the likelihood of debris flow occurrences can be much greater (or the return period much shorter) after wildfire. Many post-wildfire debris flows start in a channel as a result of high peak flows. This differs from non-fire-related debris flows in forested environments, which most often start as small debris slides that enter a channel. Hazards may be greater on “gentle-over-steep” topography, where a severely burned plateau area drains into a steep channel or gully, than on steeper, concave-up topography.

Post-wildfire landslides can occur in spring, summer, and fall in response to snowmelt, localized high-intensity rainstorms, or long-duration frontal rainstorms (Figure 9). The deforested area in a severely burned watershed can approach 100%, leading to an increased hazard of spring snowmelt-triggered



FIGURE 9 Debris flows originating in the area burned by the 2003 Ingersoll Fire near Burton (Arrow Lakes) after a long-duration, frontal rainstorm in October 2005. (Photo: P. Jordan)

events. The greatest hazard from high-intensity rainfall occurs in the first 2–3 years after wildfire; the hazard declines each subsequent year as vegetation re-establishes. The hazard caused by elevated groundwater levels during spring snowmelt can persist for many years (Jordan 2015).

In the Southern Interior of British Columbia, the areas most at risk after a wildfire are alluvial fans on which houses or other infrastructure have been built (Figure 10). In many of these areas, there is a pre-existing debris flow hazard, and the probability of a debris flow occurring increases after a wildfire. Similarly, the likelihood of a debris flow reaching the elements at risk is elevated if the size of the debris flow has increased. Alluvial fans with slopes $> 10\%$ (or as low as 5% in areas of fine-textured geology) usually have the greatest landslide risk because they are usually at least partially built by repeated debris flows.

An elevated rockfall hazard typically persists for several years following a wildfire. Rockfall in steep gullies that feed debris flow channels can be a source of increased post-wildfire debris flow hazard. Rockfall hazard that affects highways and other roads during a wildfire is usually managed by traffic control, lane closure, or total road closure. Railways are particularly subject to rockfall risks; consequently, the major railway companies have established procedures to deal with rockfall, including the increased risks following wildfire.

An increase in snow avalanche activity is common following wildfire on steep slopes in high-snowpack areas of the province, and new, long-lasting avalanche slopes can be created by wildfire (Weir 2002). Where steep slopes in high-snowpack areas have been burned, a significant snow avalanche hazard may exist.



FIGURE 10 Seasonal residence on an alluvial fan at risk from hazards on burned slopes within the 2009 Tyaughton Lake Fire.
(Photo: T. Giles)

Burned areas with the following characteristics have the potential to generate snow avalanches (Weir 2002):

- a concave profile, either down or across a slope (typically bowls or gullies) with a gradient steeper than 30° (58%);
- an adequate supply of new snow;
- a moderate exposure to wind; and
- an average depth of winter snow that is greater than the height of any rough surface features.

Snow avalanche hazard most commonly affects

highways. Where such a risk is suspected, it should be identified in the risk analysis report and referred to highways geotechnical or snow avalanche specialists.

Investigating the geomorphic hazards is the final stage in assessing the post-wildfire potential for damaging events to affect elements at risk. Where potential landslide hazards exist in or below burned areas, the preliminary landslide hazard assessment should be included in the risk analysis. Where a significant landslide risk is identified, a more detailed landslide risk assessment should be completed as soon as possible.

3 RISK ANALYSIS AND ESTIMATION

There are various types of risk analysis (Wise et al. 2004), which produce either a quantitative or qualitative estimation of risk. Partial risk is the product of the probability that a hazardous event will occur and the probability of it reaching or otherwise affecting the element at risk. It is also known as the “encounter probability” (Porter and Morgenstern 2013).

Partial risk is mathematically expressed as:

$$P(HA) = P(H) \times P(S:H) \times P(T:S) \quad (1)$$

where $P(HA)$ = partial risk; $P(H)$ = hazard or likelihood of occurrence of a specific natural hazard; $P(S:H)$ = spatial probability or likelihood of a spatial effect if a specific hazardous event occurs; and $P(T:S)$ = temporal probability or likelihood that there will be a temporal effect given that there is a spatial effect. The vulnerability or value of the element at risk is not considered for partial risk. If elements at risk from natural hazards are permanent, $P(T:S)$ is estimated to be certain (probability equals 1). Therefore, the expression for partial risk to any elements at risk from natural hazards reduces to:

$$P(HA) = P(H) \times P(S:H) \quad (2)$$

The term “probability” is used for quantitative estimates, and “likelihood” is used for qualitative estimates (VanDine 2012). Although engineers and geoscientists in British Columbia generally agree about the meaning of the rating terms, qualitative estimates of natural hazard likelihood and impact depend on the knowledge and experience of the professional. Further information on these concepts is provided in Wise et al. (2004) and Porter and Morgenstern (2013).

Under the British Columbia wildfire risk analysis procedure, partial risk is determined in qualitative terms for each element at risk and each unique hydrologic or geomorphic hazard it is exposed to.

A simple three-level classification (low, moderate, or high) is commonly used for a preliminary analysis, although a five-level classification may be used if appropriate. Generally, risk is estimated using a risk matrix that combines the two components: likelihood of natural hazard occurrence and likelihood that a natural hazard would affect an element (Table 6). Often this is done in a table (e.g., Section 5.5: 2007 Springer Creek Fire case study). Wise et al. (2004) state that the criteria for the two sets of component ratings, and the resultant risk rating, must be defined. An example of the implications of qualitative risk ratings is given in Table 7.

Risk estimation requires knowledge, training, and experience. A variety of guidelines give further information on assessing hydrologic or geomorphic risk (Association of Professional Engineers and Geoscientists of British Columbia 2010, 2012). Abbreviated examples of risk assessment after wildfire are presented in the wildfire case studies in Section 5 of this handbook.

In cases where a high partial risk of natural hazards is identified, a more detailed risk assessment of the particular site or element at risk is often recommended. Such assessments typically involve the affected stakeholders as well as responsible government agencies and local governments. Identification of significant risks may also indicate a need for risk mitigation treatments.

TABLE 6 Qualitative risk matrix for determining partial risk with three levels of risk (adapted from Wise et al. 2004)

Likelihood of occurrence of natural hazard	Risk			
	Likelihood that natural hazard will affect element:	High	Moderate	Low
High		High	High	Moderate
Moderate		High	Moderate	Low
Low		Moderate	Low	Low

TABLE 7 Example of the implications of qualitative risk ratings (adapted from Wise et al. 2004)

Risk rating ^a	Example implications for evaluation ^b
VH Very high risk	The extensive detailed investigation and implementation of mitigation treatments essential for reducing risk to acceptable levels may be very expensive or not practical.
H High risk	Detailed investigation, planning, and implementation of mitigation treatments are required to reduce risk to acceptable levels.
M Moderate risk	Tolerable, provided the treatment plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options.
L Low risk	Usually accepted. Treatment requirements and responsibility to be defined to maintain or reduce risk.
VL Very low risk	Acceptable. Manage by normal slope maintenance procedures.

a Use of dual descriptors for likelihood, consequence, and risk reflect uncertainty of the estimate, and may be appropriate in some cases.

b Implications for a particular situation are to be determined by all stakeholders; these are examples only.

4 RISK MITIGATION

4.1 Communication, Evaluation, and Treatment of Risk

The first priority during or after completion of a post-wildfire risk analysis is for the responsible agencies to warn the public, affected stakeholders, and emergency managers of any increased hazards and the immediate risk levels. Evaluation of both the acceptability of the risks and the risk mitigation options may occur subsequently, in consultation with EMBC, other responsible agencies, and/or stakeholders. If they are considered practical and beneficial within or beyond the wildfire boundary, risk mitigation treatments may then be implemented. Acting on these recommendations is the responsibility of local land managers, local government, or landowners (see Section 1.2).

Generally, the risk analysis report identifies opportunities for mitigation and may occasionally make specific recommendations for mitigation, where they are readily apparent.

4.2 Treatment Options

The objective of mitigation treatments, where the elements at risk warrant treatment, is to reduce risk to tolerable levels with cost-effective measures (see Calkin et al. 2007 for a discussion of estimating cost-effectiveness of treatments). It is generally not possible to reduce the risk after a wildfire to that of pre-burn conditions; ideally, a specific target level of risk reduction is set when deciding on treatment options for an area with elements at risk. However, due to the unpredictable nature of a number of factors, the degree or extent of risk reduction cannot be absolutely determined. These factors include, but are not limited to:

- uncertainty of climatic events;
- natural, pre-fire slope instability and related processes within the area;
- variation in treatment effectiveness;
- influence of areas that cannot be treated (e.g., areas that are too steep); and

- other land management activities within an affected watershed.

The degree of risk reduction also depends on the type and extent of mitigation treatments selected. Three general categories of mitigation measures have been defined (based on VanDine 2012):

1. removal of the element at risk (risk avoidance);
2. defensive works that protect the element at risk (changing the consequences); for example, protective structures such as dykes or berms (Hungry et al. 1987); and
3. hazard reduction on slopes within the catchment area; for example, engineering treatments to reduce the hydrologic impact of logging roads or other development in the burned area (Foltz et al. 2009), or broadcast treatments such as straw mulching to reduce the potential for runoff and erosion on severely burned areas (Robichaud et al. 2010).

This report briefly discusses categories #1 and #2 but focusses largely on #3. Experience with mitigation treatments in the Southern Interior of British Columbia informs much of this discussion and the examples. However, the experience of the U.S. Forest Service BAER operational and research staff is referenced where experience in British Columbia is limited.

4.3 Removal of the Element at Risk

Where extreme risk exists, one option is to remove the element in danger. Although this is clearly the safest option, it represents a major upheaval for a personal residence. In some cases, however, this may be the only available option that ensures the occupant an acceptable or tolerable level of risk. Residences are of particular concern because the residents are continuously exposed to the risk. Another option is to vacate a high-risk location during weather events that have the potential to trigger serious hazards.

Weather monitoring and warning systems (Cannon 2005) may have a place in mitigating some of these circumstances.

4.4 Defensive Works

Engineered structures designed to either catch or deflect a debris flow or flood within a channel or at the

slope outlet may provide protection for elements at risk such as houses, power lines, or highways. Such structures have proven to be successful in protecting elements after wildfires in the United States and in risk-prone areas in British Columbia (Hungry et al. 1987). Professional design, supervised construction, and adequate maintenance of engineered structures are often required. B.C. MFLNRO and Ministry of Transportation have used deflection berms and catch basins to protect highways and residences. Examples of such structures were used at the Terrace Mountain Fire (Figure 11) and the 2007 Springer Creek Fire (see Section 5.5).

4.5 Gully, Stream, Road, and Slope Treatments

Broad categories of treatments that are often considered (Napper 2006) include:

- in-channel gully and stream treatments that reduce water velocity, trap debris, or reduce sediment inputs into larger streams;
- road system improvement, including deactivation and drainage structure upgrading; and
- slope treatments within a catchment.

All these treatment categories have been commonly used after wildfires in the United States (Robichaud et al. 2010, 2014). In British Columbia, road system improvement is commonly used, while slope and channel treatments have been used to some extent (see Sections 5.3 and 5.5: 2009 Terrace Mountain Fire and 2007 Springer Creek Fire case studies).

4.5.1 Gully and stream channel treatments

Most channel treatments have been used in small or ephemeral streams and involve some mechanism that reduces flow rates, maintains channel characteristics, and allows sediment to settle (Robichaud and Ashmun 2012). These treatments include but are not limited to the following (see additional information in Napper 2006):

- check dams and channel stabilizing structures made of straw bales, logs, and/or rocks that are anchored in the channel;
- debris racks and catch basins upstream of critical infrastructure such as highway bridges;
- grade stabilizers (e.g., rows of boulders placed across a channel);
- use of rocks, vegetation, or engineering materials



FIGURE 11 *Debris flow deflection berm constructed to protect a residence at risk below the 2009 Terrace Mountain Fire.*
(Photo: T. Smith, Westrek)

- to protect stream banks (armouring); and
- bioengineering, which can be either a channel or a hillslope treatment (e.g., wattles that can slow overland flow and catch sediment). It is generally considered more cost-effective to mulch or place contour logs on larger, open slopes than to use bioengineering treatments.

All these treatments are generally costly, require detailed engineering, and need maintenance (Robichaud et al. 2000; Napper 2006). In British Columbia, the use of such treatments has been limited to specific types of elements at high risk. For example, B.C. Ministry of Transportation has used catch basins, debris racks, and bank armouring on some fires or post-fire problem areas where major highways were at risk (e.g., 2003 Kuskanook Fire, 2007 Springer Creek Fire [case study], and 2007 Sitkum fire).

Based on research in similar climate areas in the U.S. Pacific Northwest (Robichaud et al. 2010), it appears that treatment of severely burned slopes can reduce or prevent the need for in-channel treatments.

4.5.2 Road drainage upgrading

Inspection and possible improvement of drainage along existing road and trail systems is often a simple and cost-effective treatment. The principal concern after wildfire is that existing road systems and trail networks continue to function properly if overland and subsurface flows increase. This includes both active and inactive (non-status) roads and bladed trails and landings; it may also include features such as borrow pits and mines. In British Columbia, on-site inspections and prescriptions are generally carried out or supervised by a suitably qualified professional with experience in road main-

tenance and deactivation. For example, extensive deactivation of old roads and trails was prescribed and implemented in the 2007 Springer Creek Fire.

Watershed models developed for the U.S. Forest Service under climatic conditions similar to the Southern Interior of British Columbia may be useful in prioritizing road and trail field inspections. In a review of road treatments used by BAER teams in the United States, which included interviews with practitioners, Foltz et al. (2009) found that professional judgement and “asking a hydrologist” were most commonly used in determining design factors. The most frequently used road treatments after wildfire were rolling dips/water bars, culvert upgrading, and ditch cleaning/armouring.

4.5.3 Slope treatments

Robichaud et al. (2000) note that it is considered more effective to reduce erosion on-site by using slope treatments than to collect eroded material downstream (e.g., channel treatments). Treatments applied to severely burned slopes are widely used in the United States to reduce overland flow, sediment bulking, and resulting downslope erosion (Napper 2006; Robichaud et al. 2010). Slope and soil treatments that BAER teams have used include aerial and ground hydromulch; straw mulch; wood, including slash and mulch; chemical treatments; erosion control mats; log erosion barriers; fibre rolls or wattles; silt fences; soil scarification; and seeding (Napper 2006; Robichaud et al. 2010). In British Columbia, aerially applied and hand-applied straw mulching has been used operationally. The use of straw and wood mulches has been investigated in research trials in British Columbia (Curran and Scott 2009; Robichaud, Jordan, et al. 2013): they were found to reduce soil erosion, and the results generally concurred with U.S. results. Silt fences are not widely used in any jurisdiction except as a research tool.

Mulching In high burn severity areas, mulching can protect exposed soil from raindrop action, reduce the potential for overland flow, and increase water infiltration into water repellent and/or ash-clogged or crusted soils. Applied mulch may also enhance seed catch, seed germination, and natural revegetation. Robichaud et al. (2010) concluded that straw and wood mulches are more effective than erosion barriers (logs or wattles), hydromulches, or chemical treatments in stabilizing burned hillslopes over a range of rainfall intensities and amounts. Mulching

can work with a range of materials, on steep slopes, and even over snow if necessary.

In British Columbia, research on the effectiveness of mulching treatments has been conducted on a limited number of sites since 2003 (Curran and Scott 2009; Robichaud, Jordan, et al. 2013). Specifically, this research shows that:

- mulching treatments significantly reduce post-wildfire surface erosion;
- mulching does not significantly reduce the volume of surface runoff, although it appears to slow its velocity;
- mulching appears to be much more effective than grass seeding in reducing runoff and soil erosion, and seeding alone is generally ineffective;
- straw, bark, or wood, and burned needlefall are all effective mulch materials;
- burned needlefall offers effective erosion control with no intervention if foliage is not consumed in the fire; areas with a good coverage of fallen needles or with trees that have burned needles or leaves that will fall do not need to be mulched;
- mulch treatments should be applied as early as possible, as Year 1 reductions in erosion are generally greater than those in subsequent years;
- straw mulch should be applied at recommended rates to minimize effects on native plant regeneration (Covert 2010); and
- biological soil crusts (often a mix of cyanobacteria, lichen, and moss) can develop quite rapidly following wildfire, but their role with respect to overland flow needs further study.

Agricultural straw is the most commonly used post-fire mulch because it is generally available from agricultural lands near many fires, and it is less costly to purchase, transport, and aerially apply than wood-based mulches (Robichaud, Jordan, et al. 2013). However, wood mulch has some advantages: it is not subject to wind redistribution, it is less likely to introduce weeds, and it can be produced locally from burned trees or by adjacent logging operations, if present (Robichaud, Ashmun, et al. 2013).

Appendix 2 summarizes recommended soil mulching considerations based on experience in British Columbia to date.

Soil scarification and soil disturbance Scarification is a mechanical treatment that aims to increase water infiltration into the soil by roughening up the

soil surface and disturbing the water repellent soil layer. When combined with seeding, scarification may also help keep seeds on site until germination occurs. However, experience in the United States indicates that scarification, alone or combined with seeding, is an unreliable treatment; on many high-risk hillsides in British Columbia, it would also be expensive and difficult to achieve. Scarification may be useful in disrupting any overland flow channels that have developed on severely burned slopes. The same effect may possibly be achieved during a carefully planned post-wildfire salvage harvesting or during site preparation. However, increased mineral soil disturbance during post-wildfire salvage logging may also increase the risk of significant erosion and sediment production (Wagenbrener et al. 2015). Therefore, levels of soil disturbance should be considered in consultation with soils specialists prior to any salvage harvesting or scarification operations.

4.5.4 Revegetation, including grass seeding

Broadcast seeding, usually of non-native grass seeds, has historically been applied as a post-wildfire treatment in British Columbia. The objectives have been diverse but have often included a broad attempt to control soil erosion by increasing plant cover. Reviews of scientific evidence in the United States (Robichaud et al. 2000; Peppin et al. 2011), and to a limited extent in British Columbia, as well as operational observations, have highlighted concerns about the effectiveness of the practice and its unintended ecological consequences. In a recent review of grass seeding, Peppin et al. (2011) noted that as the quality of the studies has increased, the evidence for the effectiveness of seeding in controlling post-wildfire erosion has decreased. The authors also note that the effectiveness of seeding appears to be strongly driven by the amount and timing of precipitation. Curran et al. (2006) also suggest that grass establishment after seeding is often best on those areas where it is needed least, such as on gentle slopes and in riparian areas. In addition, grass seed does not provide a

mulching effect during rainstorms that may occur immediately post-fire. In British Columbia, in some areas too steep to mulch, seeding with a temporary cover crop such as annual fall rye grain has been used (see the Springer Creek Fire case study).

Before implementing any revegetation plans, the objectives of the plan should be clearly defined and a site analysis completed (Dobb and Burton 2013). Stark et al. (2006) suggest that seeding should be implemented only after careful consideration of the impact of the wildfire on native vegetation and its potential to recover. For broad-scale post-wildfire revegetation efforts, a plant ecologist should be involved in any decisions.

Broad-scale seeding after wildfire is often implemented to address weed control, replace or enhance forage, or affect livestock distribution (Dobb and Burton 2013). Consideration of these benefits should not be confounded with treatments aimed at reducing erosion risk.

Seeding for erosion control may be effective in areas disturbed by fire suppression activities, and is often operationally used on structures such as fireguards, fire access roads and trails, stream crossings, staging areas, and sumps.

Tree planting may be beneficial in re-establishing an earlier cover of coniferous trees, with the objective of reducing the long-term hydrologic effects of a burn, and in some cases, reducing long-term snow avalanche hazard. Tree planting was used in the 2007 Springer Creek and Sitkum Fires in the Kootenay region, in part for these purposes.

4.6 Effectiveness Monitoring

Post-treatment monitoring of soil and watershed conditions, including the effectiveness of any treatments, is important to improving both the understanding and management of post-wildfire erosion risks. Documenting specific treatment effectiveness and estimating the return on investment are necessary (Robichaud et al. 2010).

5 CASE STUDIES

Five case studies provide examples of the application of the risk analysis procedure to wildfires in the Southern Interior of British Columbia. The examples range from wildfires where only preliminary reports were completed (the Perry Ridge and Place Lake Complex Fires) to three wildfires where the risks indicated the need for a detailed risk analysis report (the Terrace Mountain, Mount McLean, and Springer Creek Fires). Risk mitigation treatments are also discussed for the Terrace Mountain and Springer Creek Fires. Known occurrences of post-wildfire landslides and floods are also reported.

5.1 Perry Ridge Fire (2013, N50196), Benninger Creek, Slocan Valley

The Perry Ridge Fire occurred in the Slocan Valley, approximately 5 km west of Winlaw, B.C., between July 24 and August 6, 2013. At the request of the Southeast Fire Centre, a risk analysis was completed (Jordan 2013), with emphasis on the debris flow risks on the Benninger Creek alluvial fan.

The fire burned 64.5 ha near the headwaters of Benninger Creek (Figure 12a). Previous mapping of terrain and natural hazards in the Perry Ridge area indicated that the Benninger Creek alluvial fan is subject to debris flow and flood hazards. Therefore, MFLNRO professionals sent a preliminary alert to the Regional District of Central Kootenay, informing them of the need to notify residents of potential hazards. The elements at risk were water intakes on the creek, and several houses on the upper part

of the Benninger Creek fan that were vulnerable to debris flows.

5.1.1 Burn severity

Risk analysis fieldwork began on the fire immediately after containment. The fire was photographed from the air, and vegetation burn severity for the Benninger Creek watershed was mapped (Figure 12b) using these photographs and additional information collected during field traverses. Table 8 summarizes the main watershed and two sub-watershed characteristics and burn impacts.

Limited ground observations indicated that water repellent soils were present in high vegetation burn severity areas, but their occurrence was patchy. It was estimated that strong water repellency occurred over about 40% of high burn severity areas and on less than 10% of moderate burn severity areas. In much of the high burn severity areas, some remnants of charred duff (forest floor) remained and soil burn severity was moderate to high. In moderate vegetation burn severity areas, soil burn severity was generally moderate.

5.1.2 Hazards

Benninger Creek was already subject to moderate debris flow hazard; existing terrain mapping, stream channel surveys, and inspection of old debris flow deposits indicated this hazard. The wildfire had only slightly increased the likelihood of a debris flow because the burn area was limited and had mostly low burn severity. Because the incremental hazard

TABLE 8 Characteristics of Benninger Creek, and its sub-watersheds, and burn severities following the Perry Ridge Fire, Slocan Valley

Variable	Watershed		
	Benninger Creek	North fork	Middle fork
Area (ha)	557	226	100
Elevation range (m)	650–2000	1090–2000	1160–1910
Relief ratio ^a	0.57	0.61	0.75
Burn area (ha) [% of watershed]	64 [12%]	37 [17%]	27 [27%]
H veg. burn severity	8 [1.4%]	5 [2.3%]	3 [2.7%]
M veg. burn severity	21 [3.8%]	12 [5.2%]	9 [9.2%]
L veg. burn severity	36 [6.4%]	20 [8.9%]	15 [15.2%]

^a See Section 2.4.3 for a discussion of the Melton relief ratio.

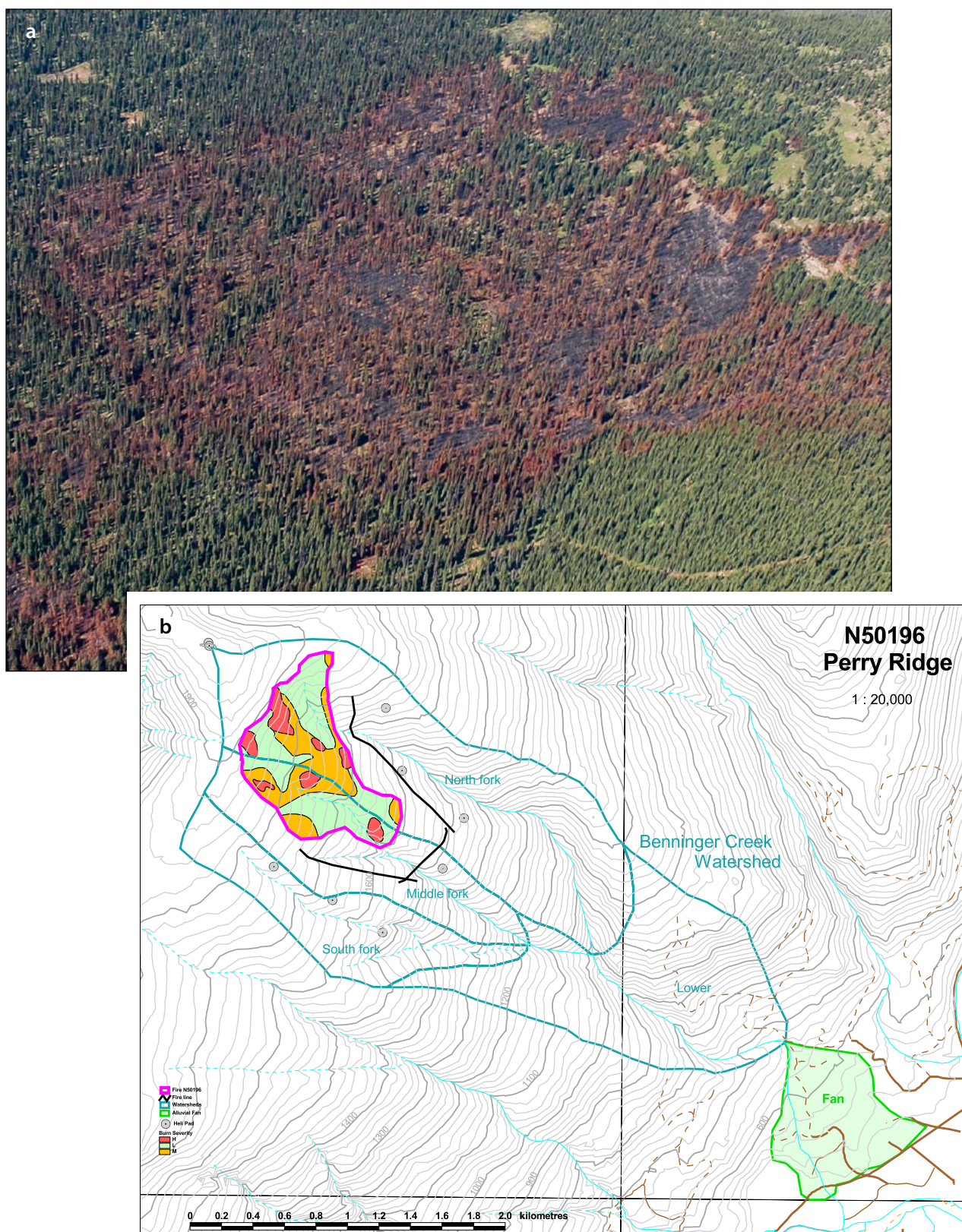


FIGURE 12 (a) Aerial view of Benninger Creek watershed after the 2013 Perry Ridge Fire, and (b) final vegetation burn severity map for the watershed. (Photo: P. Jordan)

due to the wildfire was considered to be low, the overall hazard remained moderate. A debris flow as a result of high-intensity, short-duration rainfall was estimated as unlikely because of the limited extent of high burn severity and water repellent soils; however, it could occur in an extreme rainfall event. A debris flow was considered more likely during spring snowmelt because the combined area with high and moderate vegetation burn severity, plus other openings, including areas used for firefighting, resulted in approximately 15% of the middle fork being in a near-clearcut condition.

The Benninger Creek alluvial fan is mostly a glaciofluvial fan, formed during or shortly after deglaciation by debris flows and by sand and gravel deposition by the stream. Most of the fan surface appeared to be inactive; however, the upper part of the fan has been subject to continued debris flow deposition since deglaciation. There were indications that the creek may be subject to avulsion (change of course) in a future debris flow event.

5.1.3 Risks and recommendations

The risk analysis addressed the “incremental” hazard and risk due to the fire because there already was moderate hazard and high risk to houses and water intakes on the upper part of the fan.

Two properties with houses near the apex of the Benninger Creek fan could be directly affected by a debris flow and were considered to be high consequence. The pre-fire risk to these properties was high, and the incremental risk due to the fire was moderate. Other properties lower on the fan are unlikely to be directly affected by debris flows and had moderate consequence and low incremental risk because of the fire; however, they could be affected by flooding if a debris flow were to divert the creek at the fan apex. The analysis recommended that residents of the Benninger Creek fan, especially those on the upper fan, should be informed of the debris flow risks.

A general recommendation was made that residents should be alerted about changes in streamflow or sediment in the creek that may indicate a possible debris flow. These changes included extremely high levels of turbidity or large quantities of ash or charred material in the creek during heavy rains or snowmelt; or unusual stream behaviour, such as surging or pulsing flow, or a sudden drop in streamflow.

A collection of water intakes at the fan apex that

were subject to burial or destruction in the event of a debris flow had a pre-fire moderate hazard and high risk. The hazard was slightly increased by the fire.

No risk treatments or unusual rehabilitation treatments in the watershed were recommended. Salvage logging of standing timber was not recommended because it could result in substantial increases in runoff and the debris flow hazard.

5.2 Place Lake Complex Fire (2010, C20243), Dog Creek, Chilcotin Region

In the summer of 2010, many of the fires within the Cariboo Fire Centre region coalesced into large super fires that were referred to as complexes. One of the most potentially hazardous situations was in the 7500 ha Place Lake Complex Fire (C20243). Fires were reviewed and potential elements at risk were identified using Google Earth plus any photography taken by Fire Management staff. Where there was a remote possibility of elements at risk in the vicinity of the fire, a ground inspection was conducted. Because much of the area affected by fire in 2010 was sparsely populated and has low relief, the number of elements requiring inspection was much less than areas farther south in the province.

Fifteen elements at risk were identified (Chapman and Giles 2010): three were within the fire perimeter—the Dog Creek Road, Dog Creek, and the dam on Brigham Lake; 12 dwellings or structures were identified outside the fire perimeter.

The Place Lake Complex Fire was located mainly on the relatively flat ground of the Interior Plateau; however, it also burned steeper slopes above Dog Creek, which flows through the First Nation community of Dog Creek. Most of the residences in the Dog Creek valley are constructed on alluvial fans that developed from intermittent flow off the Interior Plateau. No residences in the community of Dog Creek were identified as being at risk. However, a main access road into the community from the east was identified as being at risk.

Both sides of the road burned. There were extensive areas of high and medium severity burn on the slopes directly above the road and on the plateau above those slopes.

A summary of the hazards and risks to the Dog Creek Road and nearby recreation site is given in Figure 13, using the short form developed by MFLNRO. Risks were low to moderate, and the main action recommended was to warn the community of Dog

MINISTRY OF FORESTS AND RANGE, POST-WILDFIRE RISK ANALYSIS – PRELIMINARY REPORT

NOTE: The results given on this form are preliminary in nature and are intended to be a warning of potential hazards and risks. It is not a final risk analysis and further work may alter the conclusions. Please contact the author for more information.

FIRE: C20243, Alkali Lake Fire		FIRE YEAR: 2010	DATE OF REPORT: Sept. 16 2010	
AUTHOR: Bill Chapman and Tim Giles				
REPORT PREPARED FOR: Ken Soneff				
FIRE SIZE, LOCATION, AND LAND STATUS: 7,495 ha. Located 50 km west of 100 Mile House on TRIM maps 92O.o.60, 070 and 92P.051 and 061, the fire covers the Dog Creek watershed, which includes the tributaries of Rosetti and Pigeon Creeks. The land status is mixed Crown, several district lots and the Dog Creek Indian Reserves 2 and 3.				
VALUES AT RISK: Element 15, Dog Creek Road just East of the community of Dog Creek and the recreation site at the junction of Dog and Rosetti Creeks.				
WATERSHEDS AFFECTED: Dog Creek		TOTAL AREA 7495 ha	AREA BURNED 6300 ha	BURN SEVERITY Mixed
SUMMARY OF HAZARDS AND RISKS: For about 4 km, this road goes through areas of variably burn severity, but with considerable areas of high burn severity (see attached map). Soils include areas of silts and fine sands on slopes of 20 to 40% and which are highly erodible. <ul style="list-style-type: none"> The Dog Creek road is at risk from rocks falling onto the road from bedrock outcroppings on the north side of the road at locations R1 and R2 on map 1. Freeze thaw activity in the spring and fall may cause increased fracturing and rock blocks may fall or slide downslope and onto the road surface. In places, the Dog Creek road is located in a steep-sided melt-water channel which was incised into a flat-topped gravelly glaciofluvial terrace. The steep terrace faces were relatively stable when vegetated but removal of the binding layer of roots and vegetation has increased the rock fall potential at T5 and T6 on map 2. Rock fall is already occurring, predominantly pieces less than 20 cm diameter, but the potential for larger pieces exists in two road segments. The Dog Creek road is at risk for debris flows coming down burned draws on the north and south side of the road at locations DF3 and DF4 on map 2. On the south side (DF3), three small draws descend directly onto the Dog Creek floodplain and the potential is there for a debris flow or debris flood to impact the creek and possibly cross the floodplain to hit the road. There are 6 potential draws on the north side of the road (DF4) which have alluvial fans extending onto the floodplain of Dog Creek and reaching the Dog Creek road. <p>1. Hazard = $P(H)$, the probability of occurrence of a hazardous event 2. Risk = Partial risk $P(HA) = P(H) \times$ the probability of it reaching or affecting an element at risk</p>			HAZARD ¹	RISK ²
			low	low
			low	low
			moderate	low to moderate
FURTHER ACTIONS: The community of Dog Creek should be warned to use extreme caution when driving the Dog Creek Road or using the recreation site during periods of intense rainfall or snowmelt. Signs indicating the potential for rock falls or debris flows should be placed on the Dog Creek Road. One at the west end of the fire and the second at the junction of the 1100 Road and Dog Creek Road. There are stretches of road which are exposed to rock fall from bedrock outcroppings and sections from ravelling of steep gravelly slopes. A one kilometre stretch is exposed to an increased risk of debris flows from burned draws on the north and south sides of the road.				
POTENTIAL MITIGATION: Rock from exposed bedrock sources at R1 and R2 could be removed (scaled).				
COMMENTS:				
SIGNATURE: original signed		ATTACHMENTS: Sketch Map, Elevation Profile and BARC Map		

Southern Interior Forest Region, preliminary report form version 1.0, 22 July 2010

FIGURE 13 Risk analysis report for Dog Creek Road.

Creek about the risks when using the road and about having impaired access to their remote community, and to post signs to warn general users of the road.

5.2.1 Post-wildfire landslides, floods, and risks

Floods and/or debris flows occurred in 2011 beginning in April and peaking in June, in each of 10 drainages on the north side of Dog Creek along the identified stretch of road. The risk analysis, therefore, successfully identified the hazards and risk in this area. Debris from these events extended onto the road and blocked it for some time (Figure 14). The local garbage dump was also inundated with debris. Flooding also occurred in the spring of 2012 but not in 2013. Warning signs were placed on the road after the flooding began.

A potential deep-seated rotational failure that would have sufficient volume to block the road and Dog Creek was identified in subsequent inspections.

The slope has thus far been stable, but the risk of movement will increase as the stabilizing roots of dead trees decay. No formal monitoring of this slope is being conducted.

The professional who completed the risk analysis asked forest licensees who were salvaging timber in the area not to harvest the steep slopes leading down to Dog Creek, although there is no formal mechanism to enforce the request. The request was based on previous experience with road flooding and erosion below a fire area in the southern Cariboo. Some salvage logging occurred on the steep slopes prior to the verbal request because licensee staff were unaware of the Place Lake Fire report and the identified risks. This highlighted the need for a co-ordinated response from land managers to disseminate reports and recommendations as soon as preliminary reports are submitted.



FIGURE 14 *Deposition zone of a post-wildfire debris flow onto Dog Creek Road (berm of road in foreground), following the 2010 Place Lake Fire. (Photo: B. Chapman)*

5.3 Terrace Mountain Fire (2009, K50720)

The Terrace Mountain Fire burned an area approximately 9300 ha west of Kelowna and above Okanagan Lake between mid-July and mid-August 2009. The fire burned primarily in the Shorts Creek drainage, a relatively steep-sided creek with a rolling and gently sloping plateau area above the creek canyon.

A risk analysis was completed on the fire after several elements at risk were identified (Jordan and Curran 2009). Not all aspects of the risk analysis are presented here.

5.3.1 Elements at risk

The main focus was on two properties with houses located on alluvial fans on the south side of the Shorts Creek valley, which were considered to have the most serious potential risk of debris flows or debris slides from the burned area above. Other elements at risk that were analyzed included houses along Okanagan Lake, and a reservoir in a community watershed.

5.3.2 Burn severity

The following outlines how calibration data from the fire were used to produce a BARC map, a vegetation burn severity map, and a soil burn severity map.

Field data were collected at 60 representative sample points. Vegetation and soil burn severity class were estimated at each point, and detailed soil burn severity assessment data were collected at approximately half of the points that represented the range of burn severities. An additional 13 points in unburned forest and clearcuts were identified on air photos. Numerical values of 0–3 were assigned to the vegetation and soil burn severity classes of unburned, low, moderate, and high, respectively; burn severity assessments intermediate between two classes were also included.

A plot of the vegetation burn severity data is shown in Figure 15. From this figure, BARC values of 70, 120, and 195 were qualitatively selected to define the lower bounds of the low, moderate, and high vegetation burn severity categories, respectively (see Parsons et al. 2010 and references therein for a full

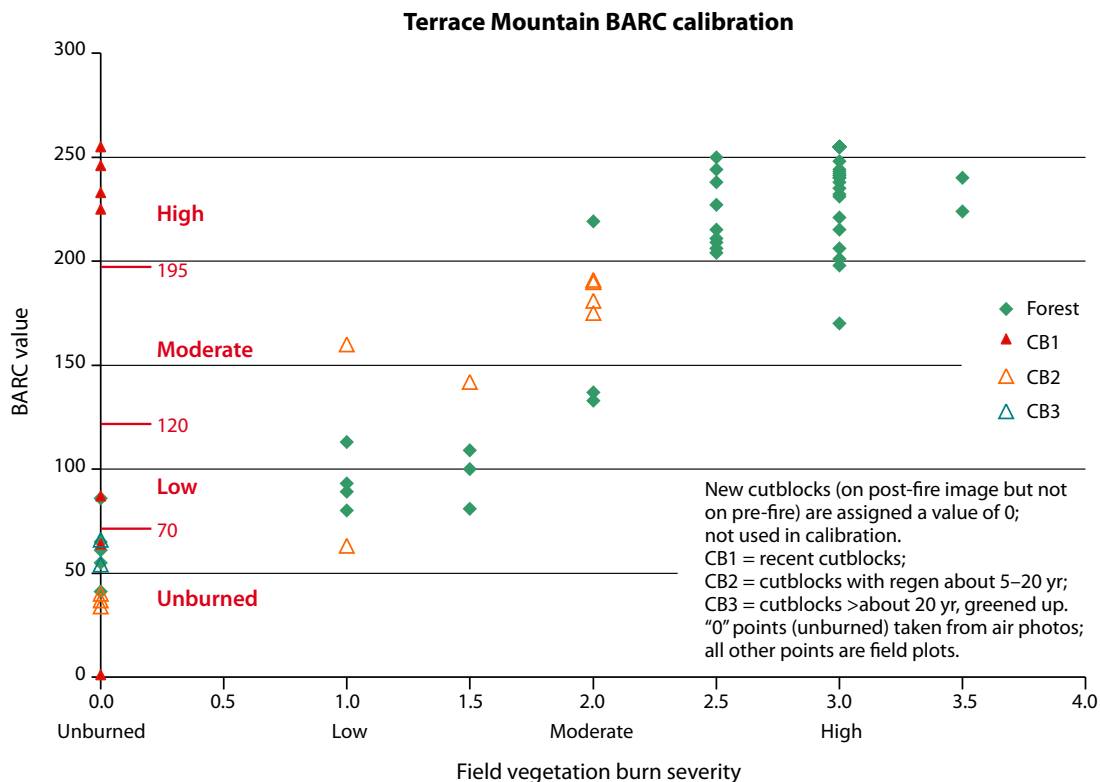
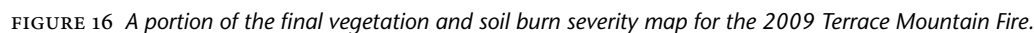


FIGURE 15 Field-assessed vegetation burn severity class and associated Burned Area Reflectance Classification (BARC) value used to calibrate the BARC map for the 2009 Terrace Mountain Fire. Vegetation burn severity values of 1.5 and 2.5 correspond to field assessments of “low–moderate” and “moderate–high,” respectively. The BARC value is the raster value for the pixel corresponding to each GPS point. The BARC value ranges selected for each burn severity class for the final map are shown on the left vertical axis.

The final calibrated vegetation and soil burn severity map for the Terrace Mountain Fire is shown in Figure 16. The effective resolution was approximately 100 m. Burned recent cutblocks were superimposed on the BARC data, and were classified as low soil burn severity.

Moderate to high debris flow hazard was identified on Wilson Creek, on several small, indistinct gullies east of Stuart Creek (both creeks are tributaries of Shorts Creek), and in the many steep, north-facing gullies and steep stream channels on the south side of the middle Shorts Creek canyon. A high hazard of post-wildfire debris floods was identified on the Stuart Creek channel and fan. Hazards were significant only where there were extensive areas of high soil burn severity above the creeks and gullies. The watersheds of these streams and gullies have “gentle-over-steep” topography, with burned plateau areas draining into steeper lower channels. Based on past experience in the British Columbia Southern Interior, this configuration is believed to be a contributing factor to high flood and debris flow hazards.

Because several houses in the Shorts Creek valley



were very close to the base of the slope, the consequence was rated as high. The risk was therefore estimated as high, and a more detailed geotechnical risk assessment was recommended. Other locations in the valley that were separated from the slope by level ground were not at any increased risk from effects of the fire.

5.3.4 Mitigation treatments

The geotechnical investigation (unpublished reports by Westrek Geotechnical Services) confirmed that houses on two properties below the fire area had very high partial risks from debris flows. Residents in one house were advised to vacate the house until risk mitigation treatments were finalized.

The reports recommended that debris flow deflection berms (Figure 11) be built to direct the debris flow path away from the elements at risk and thereby reduce the risks to low. Since the berms could be built using equipment on site for fireguard rehabilitation, costs were minimized.

Given the small area of burned slopes in one of the catchment areas, slope treatments were also recommended. In the second, much larger watershed of Wilson Creek, treating the source area was cost-prohibitive. Slope treatments that were implemented included improvement of drainage structures on the main logging road above the burned slopes, installation of cross ditches on an old logging road on a steep slope, and straw mulching of 6 ha of high burn severity slopes in the headwaters of one catchment area.

The high burn severity areas within the catchment of concern were straw mulched by hand (Figure 17) by Wildfire Management Branch unit crews in late October 2009. The aim was to provide ground coverage of approximately 70%. Only slopes < 60% were mulched, and only hollows on the slope were treated; the bedrock ridges and hummocks that separated the hollows were not treated because they were relatively unaffected by the fire. Field supervision of all aspects of the work, including straw delivery, crew guidance, on-site decisions and communication, and safety, was essential. Crew time was approximately 50 hours for a crew of 14. No helicopter time was needed. Total cost for straw mulching by hand, including supervision, was approximately \$9000 per hectare.

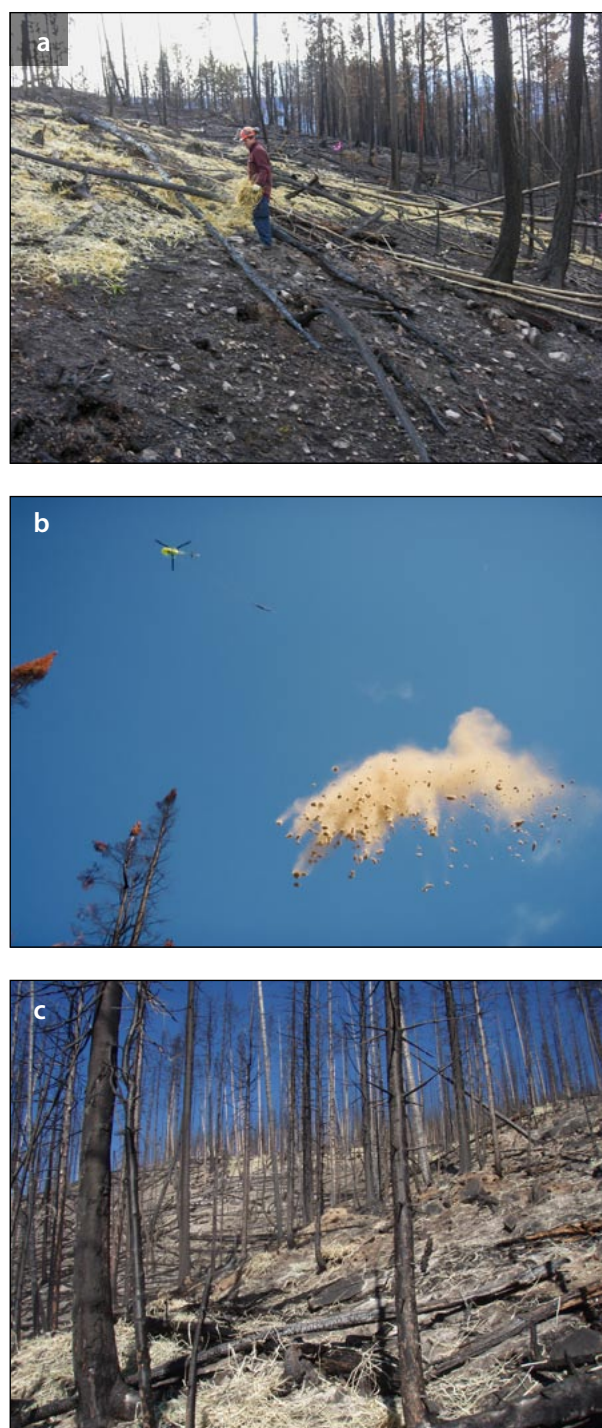


FIGURE 17 Straw mulch applied (a) by hand on the 2009 Terrace Mountain Fire and (b) by helicopter, and (c) final straw mulch coverage on an area burned by the 2007 Springer Creek Fire. (Photos: a: P. Jordan; b, c: M. Curran)

5.3.5 Post-treatment events and monitoring

A debris flow occurred in the gully of a stream above one of the houses during spring snowmelt in March 2010. The berm performed as designed and deflected the debris flow away from the house. The high streamflow that triggered the debris flow resulted from high groundwater levels and ponded water in the hollows in the upper part of the watershed. The mulching had little or no benefit in reducing runoff.

No landslides or floods associated with rainstorms occurred in the 3 years following the fire because no unusually intense rain events occurred during that period. After this time, the burned areas were significantly revegetated, and surface runoff and erosion most likely returned to pre-fire levels.

5.4 Mount McLean Fire (2009, K70814), Town Creek, Lillooet

The Mount McLean Fire occurred in July and August 2009, largely in very steep, mountainous terrain northwest of Lillooet, B.C. The area burned included 70% of the Town Creek watershed, which is immediately above the town of Lillooet (Figure 18) and the source of much of the town's drinking water. The fire

also burned along the unnamed steep cliffs above the T'it'q'et community housing on Indian Reserve (IR) # 1. The town of Lillooet and surrounding areas were evacuated when the fire spread rapidly down the Town Creek watershed. Fire management staff's initial assessment was that much of the Town Creek watershed had burned with very high fire intensity, and they were concerned about the risk to the town below. A risk analysis was begun immediately and was completed after the fire was fully contained (Hope et al. 2009).

5.4.1 General background information for the fire area

Town Creek drains a southeast-oriented watershed bordered by steep ridges on both sides. The watershed is approximately 13 km² and ranges in elevation from approximately 300 masl at the community water intake to 2288 masl at the drainage divide. The lower slopes of the watershed are moderate, with some gentle slopes along the creek, while the upper slopes are steep (50–80%) and interspersed with small flat areas. Together, the watershed's high drainage density and steep gradient suggested that there would be a rapid hydrologic response to



FIGURE 18 Aerial view of the Town Creek watershed showing residential, industrial, and recreational values, highways, and key salmon habitat downstream of the fire. (Photo: R. Winkler)

storms. Most tributaries to Town Creek are ephemeral, flowing only in spring and in response to rainstorms. Total annual rainfall in the area is low. Maximum daily rainstorms of 8–50 mm have been recorded by Environment Canada, and storms with a 2-year return period deliver approximately 22 mm of rain over 24 hours (D. Carlyle-Moses, unpublished data). Snow surveys at the nearby Mission Ridge Ministry of Environment station suggests that, on average, approximately 600 mm of water may accumulate as snow prior to melt at high elevation. Minimal snowfall may occur at low elevation throughout the winter, depending on the year.

The bedrock across the entire area is composed of a complex of metamorphic rocks. Unstable terrain is common on the steepest slopes, predominantly in the upper watershed and on some of the cliffs above the T'it'q'et community. Soils have moderately coarse textures, with very high coarse fragment content. The forest floor of undisturbed mature forest is generally 3–6 cm deep.

Forest types within the burned area varied with elevation and aspect. At the lowest elevations, there were open stands of Douglas-fir with a minor component of ponderosa pine. At mid elevations, forest cover was predominantly pure Douglas-fir. At the highest forested elevations, subalpine fir and Engelmann spruce dominated. Biogeoclimatic zones range from the Interior Douglas-Fir (IDF) at the lowest elevations, through the IDF and Montane Spruce at mid elevations, to the Engelmann Spruce – Subalpine Fir at the highest forested elevations.

5.4.2 Elements at risk

The main elements at risk from post-wildfire natural hazards were:

- District of Lillooet water intake, treatment, and storage infrastructure on Town Creek;
- public safety, houses, and infrastructure (including the Lillooet Regional Hospital) below or adjacent to Town Creek within the town of Lillooet and Indian Reserve #1, and on the T'it'q'et community housing below the “steep cliffs” south of the Town Creek watershed; and
- water quality in Town Creek.

5.4.3 Vegetation and soil burn severity

Vegetation burn severity across the fire was visually estimated from oblique aerial photographs taken during several high-level helicopter flights of the fire

area. Areas with uniform impact on the vegetation were mapped as one of four categories listed in Table 3 or as recent clearcuts. These polygons were then transferred to a base map. Ground checking of the condition of the trees and the understory was used to confirm or assist in the aerial ranking.

Soil burn severity was assessed on the ground. Field traverses were used to cover representative vegetation burn severity areas and to inspect as much ground as possible in areas of greatest concern. Mineral soil, including presence of roots, and duff (forest floor) conditions were assessed at each field site. Degree, depth, and extent of water repellency were also assessed using the water drop penetration test.

Soil burn severities assessed in the field did not directly correlate with visually estimated burn severities. Direct application of the visually derived map overestimated high soil burn severity; many areas with high vegetation burn severity were mapped as moderate soil burn severity.

High soil burn severity areas were characterized by black trees, almost complete forest floor consumption, and complete (90–100%) exposure of mineral soil. A loose 1- to 2-cm layer of surface mineral soil overlaid a better-structured soil that contained live roots. Generally, this loose surface soil was not altered significantly by the fire (Figure 19). Water repellency was generally moderate, and < 20% of any high severity area had strong repellency. Strong water repellency was found only under high-elevation,



FIGURE 19 Surface mineral soil after the 2009 Mount McLean Fire, rated as moderate soil burn severity, showing the deep ash layer, almost complete loss of forest floor, and largely unaltered mineral soil. (Photo: G. Hope)

black, subalpine fir–spruce stands that still had 0.5–1 cm of residual forest floor that would ameliorate the effects of repellency.

Areas of moderate soil burn severity were characterized by either black (predominantly) or brown trees, or were on clearcuts, and had a burned residue of thin forest floor (0.2–1 cm thick). The mineral soil structure was largely unaffected by the burn, and live roots occurred within 0.5–1.0 cm of the surface. Water repellency was generally weak and often non-existent, but patches of strong repellency occurred on up to 10% of the burned area. In moderate burn severity areas with brown trees, needlefall already covered 20–70% of the soil surface.

Within the Town Creek watershed, the approximate coverage of each soil burn severity class was as follows: high: 2–3%; moderate: 52%; low: 16%; unburned: 32% (Figure 20). Close to one-third of the watershed was burned in 2004.

5.4.4 Hazards and risks

Soil erosion and overland flow The hazard for large-scale soil erosion and overland flow in the Town Creek watershed following a high-intensity rainstorm was assessed as low to moderate based on the distribution of burn severities within the watershed, the fact that exposed mineral soil in the moderate and high burn severity areas did not show evidence of significant heating (loss of structure and live roots), and the fact that water repellency was generally weak throughout the range of burn severities. Additionally, in areas of moderate vegetation burn severity, needlefall was already providing some mulch cover. However, the hazard of small, localized soil erosion that would affect stream turbidity and water quality was high.

Hydrology The area within the Town Creek watershed that burned included most of the mid- to high-

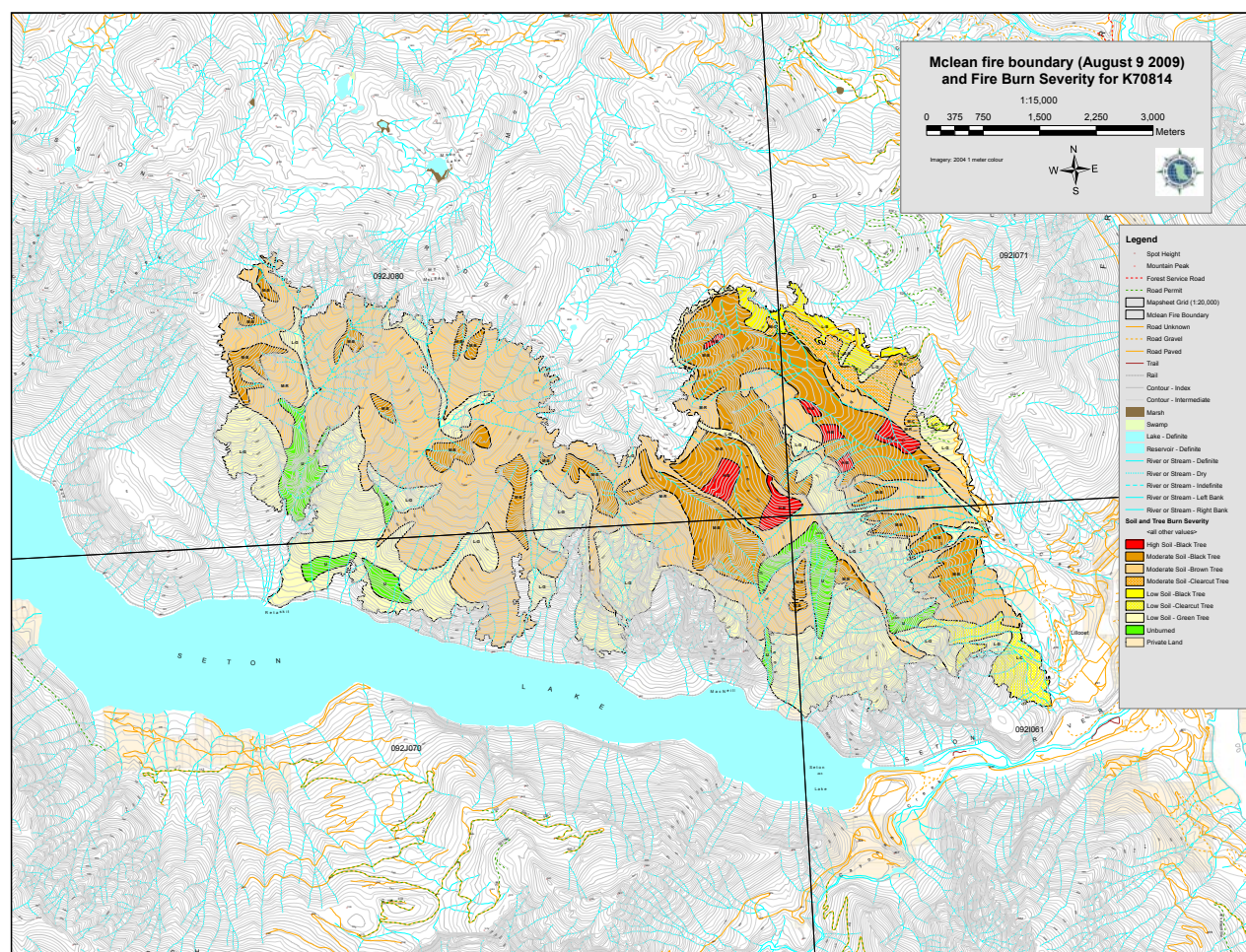


FIGURE 20 Soil and vegetation burn severity map of the 2009 Mount McLean Fire.

elevation forest, which is the primary source area for flows in Town Creek. Burn severity was predominantly moderate; however, some areas of high burn severity occurred in patches connected to the main stream channel. Very little understorey vegetation remained in moderate and high soil burn severity areas. Along the lower 1.5 km of Town Creek, the riparian zone was intact. Along an additional 1.2 km upstream into the burn, soil burn severity in the riparian zone was rated as low. Of the area that was not burned, 2% had been logged.

Landslides There were well-developed debris flow gully systems in the Town Creek watershed that showed signs of recent geomorphic activity, with alluvial cone deposits at the base of the slopes. However, debris flows appeared to be arrested on the cone surfaces where they are disconnected from the creek.

Risks The short-term risk was due primarily to the possibility of a high-intensity rainfall event in summer or fall, or rapid snowmelt in the spring. Longer-term risks related to long-duration rainfall events may have been present.

The risks to the town of Lillooet, the T'it'q'et community, and water quality in Town Creek were as follows:

- Landslides and floods

Lillooet: The risk of landslides to lower Town Creek and the village of Lillooet was low because, although the debris flow hazard was moderate, any flows had a low probability of travelling down Town Creek. A road berm on Columbia Street in upper Lillooet further lowered the probability and risk that any landslide would reach elements below Columbia Street. Because of these risk ratings, no treatments were recommended.

The risk of floods (containing eroded soil, ash, and organics) at the lower end of Town Creek was moderate. The impact of any floods on life, property, and infrastructure depended not only on rainfall amount and intensity or snowmelt rate but also on the ability of any culverts on Town Creek to conduct the expected flows. It was recommended that the capacity of all culverts on Town Creek, and the water treatment intake, be inspected by a qualified engineer. No risk or non-standard rehabilitation treatments in the watershed were recommended.

T'it'q'et community: Landslides had a moderate probability of occurring, but there was low probability

of them reaching the houses; therefore, the risk was estimated as low. The risk of floods in the small ephemeral streams that drain the cliffs above the community was considered low.

- Water quality

Risks to water quality in Town Creek were due primarily to the increased sedimentation hazard after the fire as a result of surface soil erosion or shallow debris slides close to the creek. The risk to water quality was estimated as high to very high and would most likely remain high for the next 2–3 years. Monitoring of small-scale erosion and re-establishment of ground cover in upper Town Creek was recommended, with grass seeding to follow if necessary.

5.4.5 Post-wildfire events

No major landslide events had occurred up to the late winter of 2014. Debris from any flows in upper Town Creek was arrested on alluvial fans above the main creek, although runoff from those fans did reach the creek. High freshet flows during the spring 2010 snowmelt period required diversion of Town Creek at the fan apex to prevent flooding at undersized drainage structures in Lillooet. Extreme flooding in spring 2011 again required diversion of a significant portion of freshet flows at the fan apex. Since then, drainage infrastructure in Lillooet has been upgraded.

5.5 Springer Creek Fire (2007, N50372), Slocan Valley

The Springer Creek Fire occurred northeast of the village of Slocan at the south end of the Slocan Valley, under very hot, dry conditions in August 2007. The high-intensity fire burned a steep mountainous area that is bordered on its lower western slopes by Highway 6. Several watersheds in the burned area had a long mining and logging history and a past landslide history. In addition, there were dwellings alongside the creeks that drain these watersheds, or Highway 6 crossed over those creeks. Therefore, a risk analysis was completed at the request of the Southeast Fire Centre (Nicol et al. 2007).

5.5.1 General background information for the fire area

The fire area is located between approximately 550 and 1930 m elevation on generally west-to-north-west-facing slopes above Highway 6 and Slocan

Lake. Highway 6, a major travel corridor along the lake, extends in a north–south direction at approximately 700 m elevation. The terrain between approximately 750 and 1600 m elevation is characterized by steep slopes (55–120% gradients), several deeply incised v-shaped gullies, and isolated rock cliffs (Figure 21). Above these steep areas are more gentle slopes that constitute the headwater areas for the various creeks and gullies. The local bedrock is predominantly granite. Soils derived from these rocks typically develop a sandy matrix with a high percentage of coarse fragments.

The burned areas drain north into Enterprise Creek, west into Allen Creek, Cory Creek, and Van Tuyl Creek, and south into Memphis Creek. All of these creeks drain into Slocan Lake. In addition, several rocky face units burned. Many of the watersheds have a documented history of debris flow and debris slide activity that has often had an impact on Highway 6, water systems, and buildings. Previous work had shown that 12 debris flows had occurred between 1958 and 1990 in the Cory, Van Tuyl, and Memphis Creek drainages.

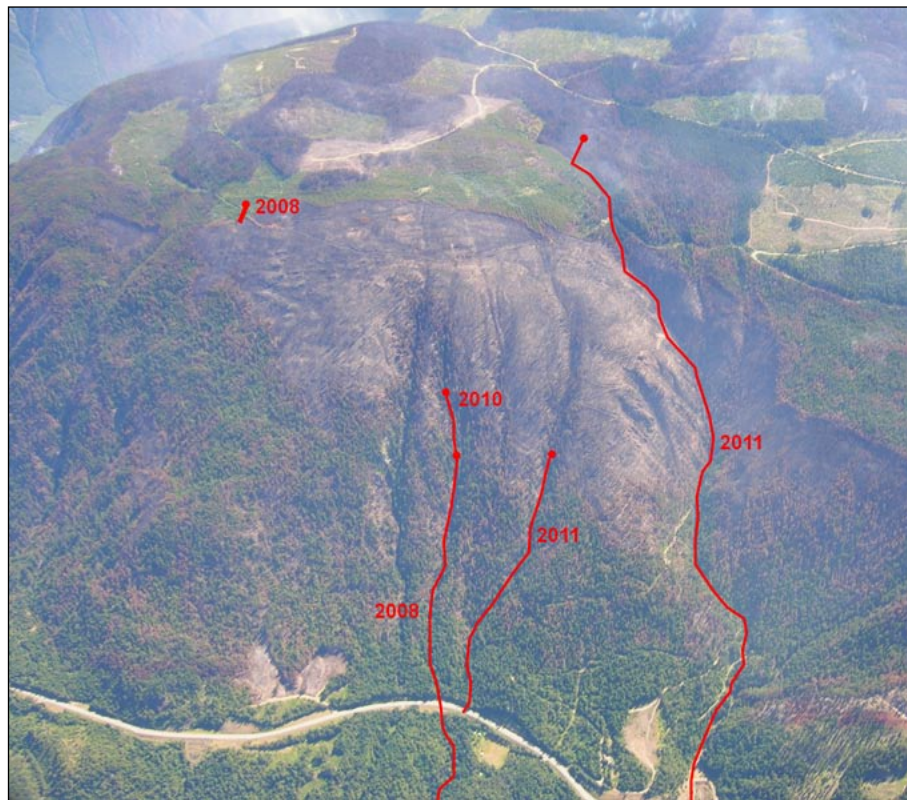


FIGURE 21 Burned slopes within the 2007 Springer Creek Fire, and debris flows following the fire, with slide tracks marked. (Photo: P. Jordan)

The Interior Cedar – Hemlock BEC zone occurs at low elevations, and the Engelmann Spruce – Subalpine Fir zone occurs at higher elevation within the fire area. The area was significantly logged over the previous 30 years; consequently, an extensive network of logging roads and trails cover the area.

5.5.2 Elements at risk

As well as Highway 6, many houses and water intakes are located on a broad bench below the steep slopes burned by the fire. Because of their location and the debris flow history in the area, they all were identified as elements at risk. A summary of the identified elements and their hazards is given in Table 9. For brevity, other creeks, slopes, or rock faces that were subsequently identified as low hazard are not reported here.

5.5.3 Vegetation and soil burn severity

A preliminary visually derived vegetation burn severity map was prepared from high-altitude, oblique aerial photographs, using the classes shown in Table 3. The map was then tested with ground calibration

checks. Soil burn severity (Table 5) was assessed based on field data collected at each ground calibration point. The vegetation burn severity map (reduced in scale) is shown in Figure 22. The field data indicated that soil and vegetation burn severity were highly correlated in most of the fire area. However, field checks indicated that, within several drainages, some of the area mapped as low vegetation burn severity had a moderate to high soil burn severity, most likely as a result of creeping ground fire or underburning in those areas.

About 80% of plots in high vegetation burn severity polygons had strong and extensive water repellency (i.e., most of an inspection trench was repellent), and all had high soil burn sever-

TABLE 9 Summary of elements at risk, terrain hazards, burn, and risk for selected drainages in the Springer Creek fire area, Slocan Valley

Creek	Area (ha)	Element at risk	Primary hazard	H and M burn severity (%)	Partial risk ^a
N Cory	91	House and highway	Debris flow	39	H
S Cory	48	Houses and highway	Debris flow	34	H
S S Cory	45	House and highway	Debris flow	38	H
S Van Tuyl	86	House and highway	Debris flow	57	H
Enterprise 1	49	Highway and crossing	Debris flow	83	H
N Van Tuyl	80	Highway	Debris flow	73	H
Mid Van Tuyl	26	Highway	Debris flow	43	H
Allen	70	Houses and highway	Debris flow	27	M–H
S end of Face Unit R5		Highway and houses	Debris slide or debris flow	50	M–H
Memphis	539	Highway	Debris flow (or floods)	52	M
S Memphis	211	Highway	Debris flow	29	M
Enterprise	12000	Highway crossing	Debris flood	4	L

a Sorted in order of risk severity (H: high; M: moderate; L: low) and therefore treatment priority.

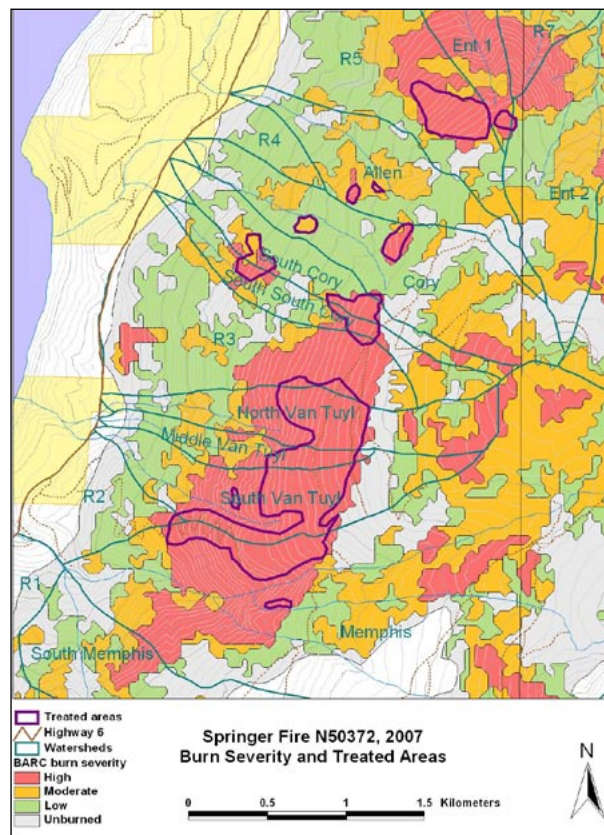


FIGURE 22 Mulch treatment areas (within purple lines) overlaying the 2007 Springer Creek Fire burn severity map. Approximately 110 ha were recommended for treatment.

ity. In “moderate” and “low” polygons, about 45% of plots had strong water repellency, although those plots were usually located in more heavily burned patches.

5.5.4 Hazards and risk

High burn severity polygons were considered to have a high likelihood of overland flow during heavy rain; where such areas were large and contiguous, overland flow could cause debris flows or flooding in the channels below. This hazard was less in areas of moderate burn severity because of both the patchy nature of the burn and the potential for natural mulching from needlefall.

To ensure that roads and trails did not promote concentration or diversion of surface flows, or overland flow from burned areas, existing operational forest roads, fire protection constructed guards and structures, and old roads and trails located in the headwaters of several creeks were identified for review and deactivation, if required.

Possible post-wildfire hazards in the drainages within the fire area included debris flows in steep creeks and gullies in and below the burn areas, open slope debris slides, debris floods on larger, low-gradient creeks, and rockfall. After assessment of the degree of burn severity, gully characteristics, potential supply of debris flow volume, historical debris flow deposits, and old landslide reports, the likelihood of a landslide or flood (the hazard) in each

of the drainages was estimated. The consequences of hazard occurrence, determined largely by estimating if the hazard would reach the element at risk, and the location of that element, were combined with hazard likelihood to produce partial risk estimates (Table 6) for each watershed area within the fire.

In the Memphis Creek watershed, a risk of increased spring peak flows and frequency of flood events was identified due to the large area of moderate-severity burn combined with an existing, large pre-fire equivalent clearcut area.

The possibility of increased snow avalanche risk above Highway 6 was identified due to the loss of the forest canopy in an area of steep slopes, conducive terrain features, and high snowfall.

5.5.5 Risk analysis recommendations

The following are some of the treatment recommendations from the risk analysis and subsequent mitigation plan:

- All mining and forestry roads and trails located in and above the high-risk areas should be ground reviewed and adequately deactivated to ensure that they did not cause further concentrations or diversions of surface or overland flow.
- Slope treatments that involve mulching with straw and seeding with a fall cereal grain should be applied on burned areas at the headwaters of the high-hazard gullies above high-risk locations. The total proposed, feasible mulching treatment area was about 110 ha, on three high-priority public safety risk types: 1) to residents (65 ha); 2) to the travelling public on or near main highway creek or culvert crossings (2.5 ha); and 3) to the travelling public elsewhere along Highway 6 (41.5 ha). The area feasible for seeding was approximately 140 ha. It is not feasible to treat the steepest slopes in some watersheds, particularly the heavily burned gully headwall areas in Allen Creek and most of the Enterprise 1 tributary.
- The effectiveness of protection devices such as diversion berms, catch basins, or other structures located above houses, private property, and Highway 6 should be evaluated. Also, consideration should be given to evaluating various early warning systems and monitoring local weather data.
- The B.C. Ministry of Transportation should review existing and proposed highway infrastructure below high burn severity areas.

- An avalanche risk assessment should be conducted above Highway 6.
- Potential starting zones of snow avalanches should be reforested as soon as possible.
- Salvage logging should not proceed in the high or moderate hazard watersheds above elements at risk unless a further detailed study indicates that such harvesting would not exacerbate or concentrate increased surface water or overland flows.

5.5.6 Risk mitigation

Treatment decisions The Springer Creek fire was the first opportunity for B.C. Ministry of Forests and Range (MOFR) professionals to develop a plan for mitigating the high risk to people and infrastructure below a burned area. The MOFR staff consulted widely, particularly with U.S. Forest Service specialists experienced in treatment of high-risk burned areas.

For areas outside MOFR responsibility, a recommendation was made to evaluate the effectiveness of structures to protect elements at risk (see Risk analysis recommendations above). The B.C. Ministry of Transportation, which is responsible for Highway 6, constructed catch basins and overflow culverts at several potential debris flow sites, and replaced a major culvert on Enterprise Creek.

For areas under MOFR management, both in-channel and slope treatments were considered. Based on U.S. Forest Service experience, and for many of the reasons discussed in Section 4 it was decided that the best risk reduction options available to the MOFR were mulching of high-hazard slopes, deactivation of roads and trails in and above the high-risk areas, and tree planting to mitigate longer-term risks.

Treatments within the Crown forest area

Roads: Those responsible for status roads (i.e., B.C. Ministry of Forests Districts and forest licensees) within high-hazard areas were advised to evaluate if any drainage upgrades or road deactivations were necessary. An inventory of non-status roads, and where required, deactivation upgrading of those roads, was recommended. Approximately 20 km of non-status roads, including old mining roads, were inventoried, and where necessary, had cross-ditches installed. Deactivation of some skid trails, and additional cross-ditching of previously deactivated logging roads, was also conducted in the high-risk area.

Mulching and seeding: Treatments were planned, approved, financed, and applied. Figure 22 shows

the mulch treatment areas overlaid on the Springer Creek Fire burn severity map. The experience with these treatments formed much of the basis for the more detailed advice on mulching given in the Appendix 2. The following is a brief summary of the slope mulching treatments that were applied:

- Mulch was applied by helicopter. The objective was to have 70% coverage of the soil with mulch to a depth of 2.5–5 cm. Helimulching was applied on slopes up to 60%, and even on slopes up to 70% in the most critical areas, at a rate of 3.75 tonnes/ha (1.5 ton/acre).
- High-risk areas were additionally seeded with cereal rye on slopes up to 70%, with or without mulch. The seeding rate was 15 kg/ha outside of mulching areas, and 10 kg/ha within.
- The cost of applying the mulch was approximately \$2000 per hectare, not including ground crew costs. The seeding cost was approximately \$80 per hectare.
- Three main types of straw were tested: tall fescue hay in 3 × 3 × 8 foot bales—spread well; cereal grain (mainly wheat) in 4 × 4 × 8 foot bales—spread was variable; and canola in 4 × 4 × 8 foot bales—spread well.
- Operations involved two helicopters with a minimum of four nets averaging 6 minutes per turn, and a ground operation of one four-wheel-drive tractor (with forks) and operator, six fire crew members, and a supervisor.
- Some soil hand-scarification, largely cross-drainage of rills, was completed prior to mulching in areas where erosion rills had begun.

5.5.7 Post-wildfire events

The first debris flow off the Springer Creek fire area occurred in the Enterprise Creek drainage on August 31, 2007. In the 4 years after the fire, a number of debris flows occurred, including eight that were large enough (1000–5000 m³) to reach the valley bottoms and block highway culverts or logging roads (Figure 21). In Middle Van Tuyl Creek in the spring of 2008, three debris flows occurred on successive days, one of which caused a fatality; they also

filled the ditch catch basins and covered the highway.

The investigation into the fatal event found that there were two significant causes of the debris flow, which occurred during a period of hot sunny weather at the peak of snowmelt. The total snow accumulation and the peak melt rate had increased in the burned area in the headwaters of the drainage area, and an old logging landing had caused a diversion of runoff into Middle Van Tuyl Creek from the adjacent drainage. The debris flows originated in the creek channel where it steepened to a critical slope of about 37°, and were caused by increased peak flow in the channel. There was negligible surface erosion in the burned area.

In May 2010, another debris flow occurred in the same channel. In May and June 2011, additional debris flows occurred in two nearby channels, South Van Tuyl Creek and Memphis Creek. All these events occurred during spring snowmelt. In hindsight, the straw mulching, which was applied to reduce the hazard during summer rainstorms, had no effect during snowmelt. Another contributing factor to the debris flows may have been the loss of stabilizing large organic debris in gullies.

In the Enterprise Creek valley, four significant debris flows, and several minor ones, occurred in steep gullies in the late summer and fall of 2007, 2008, and 2009. These gullies are fed by rockfall, and had previously experienced occasional debris flows that blocked the logging road in the valley. One of the post-wildfire debris flows occurred during a heavy 2-day rainstorm (50–75 mm at nearby rain gauges), which was approximately a 10-year event in terms of total rainfall. The other debris flows occurred in response to very minor rainfall events, as recorded by rain gauges, but it is possible that local, unrecorded, heavy rain occurred. This area was identified as low risk because it has no residents or infrastructure.

Six rain gauges were installed in the burned area after the fire, and operated for 4 years. Other than the one rainstorm noted above, no rainstorms occurred that exceeded an estimated 2-year return period, for either 1-day rainfall or short-term (10–60 minute) rainfall intensities.

6 SUMMARY

The post-wildfire natural hazards risk analysis procedure represents a systematic approach for assessing risks to public safety and infrastructure from soil erosion, floods, landslides, and snow avalanches following a wildfire. This Land Management Handbook describes the process of conducting such an assessment. Screening wildfires, identifying elements at risk, establishing assessment teams, and gathering background data are the necessary first steps. Assessment of post-wildfire vegetation and soil conditions is critical because it leads to the development of a calibrated soil burn severity map for the area burned and provides a basis for predicting soil erosion and assessing hydrologic and geomorphology hazards. Experience on wildfires in British Columbia should inform the hydrogeomorphic considerations made during field review and any assessment

of these hazards. Downslope and downstream risks to life, property, and infrastructure are then qualitatively estimated and communicated to affected stakeholders. Risk mitigation treatments may then be implemented; road drainage upgrading is a common treatment and mulching of burned slopes has been used in limited areas in British Columbia. The procedures discussed in this handbook provide a minimum set of considerations for any post-fire assessment and define the process of evaluating risk. Other published sources of relevant burn severity and hydrogeomorphic information are also identified. Steps in this procedure will be refined as experience is gained over a broader range of fires and landscapes and as new post-wildfire research becomes available.

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APPENDIX 1 Burn severity field forms**BURN SEVERITY ASSESSMENT (short form)****FIRE** _____

Plot number: _____ GPS #: _____ Crew: _____ Date: _____

GPS coordinates: _____ Elevation: _____

Slope: up _____ % down _____ % Aspect: _____

Canopy condition (circle one class)				
Unburned	Mostly alive (green)	Mostly dead; needles remaining (brown or red)	Dead; no needles; some twigs and cones (black)	Dead; trunk and large branches only (black)

% Cover: Green understorey: _____ % Green trees: _____ % Brown trees: _____ %

Vegetation burn severity:

Low

Moderate

High

Soil burn severity indicator	Indicator class (circle one)		
Litter	scorched, charred	mostly consumed	consumed
Duff (FH layers)	intact	spottily consumed	mostly consumed
Woody debris – Small	charred	partly consumed	consumed
Woody debris – Logs	charred	some consumed	many consumed, others deeply charred
Ash colour (if present)	black	grey	white
Mineral soil exposure	<5%	5–40%	>40%
Change to mineral soil (structure, colour, etc.)	no	minor	yes
Depth to live roots or rhizomes (in min. soil)	0	0–5 cm	>5cm

Soil burn severity:

Low

Moderate

High

Size of surrounding area similar to plot: <½ ha ½–2 ha 2–5 ha >5 ha

Evidence of runoff/overland flow: sand deposits needle deposits rills pedestals terracettes

Water repellency – extent and class:

Results from dripping water along a 0.5–1 m trench exposing the repellent mineral soil layer:
 record **Water Repellency Class** based on the time required for the absorption of a drop of water on dry soil and % of the trench in that class (Add columns to right if testing more than one depth).

Trench depth: _____ cm
 a. None – <10 seconds _____ % of trench
 b. Weak – >10 and <40 seconds _____ % of trench
 c. Strong – >40 seconds _____ % of trench

SOIL BURN SEVERITY ASSESSMENT (detailed form)

Fire: _____ Date: _____ Crew: _____
Stratum: _____ GPS: _____
Plot: _____ Representative area (ha): _____

Site, Soil, and Vegetation Characteristics

Terrain and soil type: _____
BEC: _____
Aspect: _____ Slope angle: _____
Pre-fire forest cover: _____
Vegetation burn severity class: _____
Other (overland flow, rills, sediments): _____

Forest Floor Assessment

Forest floor depth (cm): pre-fire: _____ post-fire: _____ % cover: _____
Condition of large wood debris (charred, consumed, etc.): _____
% cover of woody debris: _____
% cover of needle cast: _____

Mineral Soil Assessment

Surface soil texture and colour: _____
Surface coarse fragment content: _____
Ash colour and depth: _____
% mineral soil exposure: _____
Depth in mineral soil to live roots or rhizomes: _____
Soil burn severity class: _____

Water Repellency Assessment

Soil moisture condition (dry, moist, wet): _____
Short duration water drop penetration test

- Thickness of any wettable surface soil layer: _____
- Depth at which repellent soil is found (e.g. 0–3 cm below surface): _____
- Thickness of repellent layer: _____

1. Repellent layer horizontal extent:

Length of line: _____ Number of points: _____

2. Repellency class and proportion:

None (0–10 sec)	Weak (>10–40 sec)	Strong (>40 sec)
Average time:	Average time:	Average time:
% of line:	% of line:	% of line:

3. Infiltration: using the mini-disk infiltrometer at 3–5 locations at each plot

- Time to first bubble

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- Volume infiltrating in one minute (mm/min)

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This appendix summarizes some lessons learned from the application of agricultural straw mulch to burned slopes in British Columbia. Its purpose is not to replace the detailed information available in U.S. Forest Service publications (Napper 2006; Robichaud et al. 2010) but rather to augment them with information suitable for British Columbia soil, climate, and administrative conditions. The intent is to facilitate implementation of site-specific post-fire mitigation plans. The intended audience is individuals involved in preparing and/or implementing post-fire risk mitigation projects.

The objective of the treatment described here is to cover severely burned areas of bare soil with sufficient mulch material to mimic the role of the natural forest floor in protecting the mineral soil, and to limit overland flow and soil erosion. Although a number of mulch materials are effective in meeting this objective, experience in British Columbia suggests that a thin uniform cover of straw is an effective and relatively simple way to achieve this objective on severely burned, high-risk slopes and catchment areas.

A. Straw materials

- Identify sources of appropriate straw as soon as a risk treatment is being discussed and before final reports are completed. Straw availability may be limited if it is needed prior to the late summer/fall harvest period.
- Any straw material will work except for flax, which is sticky; however, some materials are lighter than others and thus more susceptible to being blown about in windy locations. If the site has a very high potential for wind disturbance, investigate which straw or hay may be less likely to blow around (e.g., some types such as fescue or canola may stay down or interlock more).
- Certified weed-free straw is the most desirable to ensure that invasive plants and/or noxious weeds are not being introduced. Because weed-free certification is not readily available in Canada, consult with other programs about how to obtain straw that is as weed-free as possible; straw from a seed producer may be an option.
- Bale types are dictated by application method. For hand application, standard small bales are

best. For helicopter application, large rectangular bales are best. Round bales are more difficult to work with; they require extra cutting with chain saws and fluffing with forks to ensure spread during helicopter application.

- Straw should be dry for best application; wet straw is heavier, can be mouldy, and can clump together during either hand or helicopter application. Ensure that straw is covered if there is any risk of precipitation during transport or storage/staging. Straw can also absorb moisture from wet ground or groundsheets. If straw is damp, crews will have to cut bales (with a chainsaw) and fluff it for helicopter application.
- To achieve the prescribed coverage, required application rates of dry straw are approximately 3.75 tonnes/ha (hand or aerial), or heavier if the straw is damp.

B. Applying mulch

- Timing is critical because of the narrow time window after the fire is controlled and before wet fall and winter weather conditions occur.
- Co-ordinating the mulching treatments with routine post-wildfire rehabilitation of fireguards, etc. will help minimize costs; that is, when crews, equipment, and supervisors are available on-site or when other treatments such as drainage improvement are being implemented.
- In British Columbia, straw has been applied by hand and from helicopters (Figure 17b); blowers are also used in the United States. Helicopter application is best for larger, contiguous areas > 5 ha, or slightly smaller areas if they are linear in shape, because of the airspeed required to obtain sufficient spread. Ground application is preferred for small areas < 3–4 ha. However, large crews are required for hand application, and this method may be costlier than helicopter application when all costs are considered. U.S. guides provide some cost estimates, but their costs per hectare may be lower because the treatment areas are relatively large compared with those in British Columbia.
- The prescribed application rate is normally 70% coverage with 2.5–5 cm depth of straw (1–2 inches). It is easier for crews to strive for “3/4 of an area covered” (Figure 17c). There should be

fairly uniform, thin coverage, without many large clumps or large bare patches. Coverage should be just enough to break the force of raindrops; if it is too thick, it will inhibit natural revegetation.

B.1 Hand application

- This method works best if mulching small areas, either one area or several patchy, dispersed areas.
- Treatment areas should be surveyed and flagged. Stony ground should be included in the treatment, and mulch should be applied up to the edge of bedrock (or where no surface litter existed pre-fire).
- If good access is available for ATVs and other vehicles, they can be used to transport straw for hand application. If not, a helicopter can be used to sling the straw into key areas for further distribution/application by hand crews.
- The optimum ground crew size is likely about the same size as a helicopter mulching ground crew (e.g., 10+ persons).

B.2 Helicopter application

- An appropriate helicopter with sufficient lift and manoeuvrability is required for both efficiency and safety.
- Treatment areas may require marking (e.g., with wide flagging tape) to ensure that they are visible from the air.
- Mulch coverage, but not depth, can be estimated from a helicopter. Experience indicates that having the pilot aim for 100% coverage ensures that the required depth over 70% of the area is obtained.
- Clumping during application, pilot inexperience, wind, animal traffic, and snow creep, can all result in uneven distribution of the straw. Heavy application rates will ensure better distribution.
- A front-end loader/tractor is required to unload trucks and load the large bales into the helicopter nets.
- The location of the staging area is important. If the optimum staging area is unreachable by highway transport trucks, consideration should be given to off-loading the straw onto smaller trucks for final delivery.
- Costs are difficult to estimate because they depend on a number of factors, including source location of the straw, trucking logistics, size and operability of the area to be treated, location of the staging area, moisture content of the straw,

efficiency of loading the straw into nets, and weather.

C. Other considerations

Crew needed

- Supervisor: An on-the-ground technical supervisor who understands the technical prescription needs to be present daily to supervise all aspects of the treatment, including making adjustments as new issues arise. The amount of supervision required depends on the complexity of the treatment areas and terrain.
- Danger-tree fallers will be needed for staging areas for all methods of application, and may be needed in areas beyond staging locations for hand application.
- Hand mulching requires a relatively large ground crew; experience from the 2009 Terrace Mountain Fire suggests a crew of 6–10 is efficient. However, depending on the project size, the crew may be required for a longer period than for aerial application.
- For aerial application, a crew large enough to support the helicopter is required. In order to keep several nets operating, the optimum ground crew size is about the same size as a hand mulching crew (10+ persons). An additional person in the vicinity of the mulched area can provide helpful feedback to the helicopter pilot.

Safety

All normal wildfire management safety practices should be followed, including those involving helicopters. Danger trees around helicopter staging areas and in hand application areas will need to be removed. There is also a risk for ground crews of slipping on wet, burned soils or on mulched areas. Any ground crew near active heli-mulching also needs adequate visibility, radio contact, and awareness of the danger from clumped falling straw.

