Wet Weather Shutdown Criteria

MFLNRORD Southern Engineering Group

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EARTH WATER LAND

EXECUTIVE SUMMARY

BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development (MFLNRORD) requested that Statlu Environmental Consulting Ltd. (Statlu) review existing wet weather shutdown procedures for the southern Interior of British Columbia, compare them to guidelines in use in other comparable areas of BC, and develop a consistent and scientifically based procedure to guide wet weather shutdown across the southern Interior.

This document consists of three components. The first is a review of relevant scientific literature and research, a review of existing shutdown criteria used in the BC Interior and relevant procedures used elsewhere, and a discussion of the theory and practice of wet weather and environmental shutdown criteria, in particular dealing with problems of measurement and interpretation that have reduced the effectiveness of shutdown criteria previously used in other areas.

The second component consists of an analysis of predicted annual precipitation, rainfall, and snowmelt, as well as potential rainfall and snowmelt intensities and durations at specific frequencies for various locations across the southern Interior of British Columbia.

The third component is based on the first and second components and includes recommended shutdown criteria for the southern Interior of British Columbia, based on observed or predicted rainfall and snowmelt and stratified by total annual precipitation and the presence or absence of unstable upslope conditions, including recent past forest fires.

The third component can be developed into a stand-alone document for circulation to forest workers, government contractors, and forest licensees for their use in determining whether or not environmental conditions warrant shut down of operations to protect worker safety.

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1.0 INTRODUCTION

The BC Ministry of Forests, Lands, Natural Resource Operations, and Rural Development, Southern Engineering Group (MFLNRORD) retained Statlu Environmental Consulting Ltd. (Statlu) to develop guidelines for wet weather shutdown of forestry operations for the BC Interior. Currently, there is a lack of consistent criteria providing guidance for workers to determine whether environmental conditions have increased hazards, or to evaluate under what conditions they might wish to stop work during or resume work after such conditions occur. A consistent set of guidelines that provide consistent direction for workers and regulators as to whether forest operations should proceed or shut down in wet weather will increase safety and ease implementation across the region.

2.0 THEORY OF ENVIRONMENTAL SHUTDOWN CRITERIA

Hazardous geotechnical processes are more likely to occur under some environmental conditions than others. Specifically, many mass movement processes, such as landslides and debris flows, occur when the ground is unusually wet because increased pore water pressure in surficial materials and fractured bedrock decreases cohesive forces, which increase slope instability. In Interior British Columbia, decreased terrain stability most commonly occurs during or immediately after three environmental conditions (Jordan, 2015):

- Spring snowmelt, possibly modified by rainfall;
- Intense, short-duration summer precipitation; or
- Less-intense but longer-duration precipitation in summer or fall.

Environmental shutdown criteria are determined by defining conditions that are likely to result in mass movements. Typically, the criteria use the amount of precipitation or precipitation equivalent over a period of time to set thresholds. When there is more precipitation than the threshold, field work is shut down, limiting worker exposure to precipitation-driven terrain hazards.

Climatic variation makes it difficult to define unusually wet conditions. A precipitation or snowmelt that is large enough to be significant and to cause landslides in dry parts of the province is neither unusual nor significant in wetter regions because landscapes adapt to the prevailing environmental conditions. Regions which are characteristically wetter, such as the Interior Wet Belt of the Kootenays and Cariboo Mountains, require more precipitation than drier inland or sheltered areas, such as Cache Creek or Penticton, to trigger landslides.

A number of other factors complicate the issue and make it difficult to define simple, broadly applicable criteria for environmental shutdown. In addition to the climatic factors already identified, antecedent moisture conditions, the nature of surficial materials and bedrock present, the contribution to ground moisture from snowmelt and rainfall, the spatial variability of precipitation at different scales, the varying intensity of precipitation, and the varying timing of response of shallow and deep groundwater to climatic forcing all contribute to the likelihood of mass movement. Of these factors, antecedent moisture conditions are perhaps the hardest to adequately account for. Finally, climate stations in British Columbia are scattered in space and have discontinuous temporal records. They are usually located in low elevation valley bottoms and mostly absent from high elevation mountainous locales. Models and inferences must be used to refine uncertain estimates, especially in areas without measured climate values.

Environmental shutdown criteria are intended to reduce the risk to workers from unstable terrain. The mass movement events themselves do not create the risk, the potential exposure of workers and equipment to them do. If shutdown criteria are too stringent, work will be needlessly shut down, incurring an economic cost, and possibly making workers and managers less likely to follow shutdown procedures in future. Conversely, if shutdown criteria are too lenient, workers, vehicles, and equipment will be at placed at unacceptable risk of injury or death, and damage or destruction respectively.

3.0 REVIEW OF RELEVANT RESEARCH AND DISCUSSION

There has been considerable interest in using environmental shutdown criteria to manage risk, both in British Columbia, and internationally. Caine (1980) was one of the first to propose a simple criterion in the form of an equation relating intensity and duration of rainfall. Caine's proposed equation indicated that approximately 100 mm of rain over 24 hours was likely to cause landsliding or debris flows. The relationship was based on a wide range of climates and terrains, and consequently there was scatter in the data points from which the equation was derived. Church and Miles (1987) examined thresholds for debris flow initiation in British Columbia and found that, due to the unrepresentative nature of the climate station network, a threshold value of 50 mm of rainfall in 24 hours measured at a climate station was a predictor of landslides and debris flows in nearby mountainous terrain. Howes (1987) noted that for the southern Coast Mountains near Norrish Creek, estimated one-day and three-day precipitation totals for storms with an approximate one-in-ten year return period were respectively 93 mm and 123 mm, and that it was storms of approximately this frequency that typically triggered extensive landsliding and debris flows. This was an important early acknowledgement that storm frequency (return period) might be a better predictor of instability than storm magnitude (precipitation total). Slaymaker (1990) criticized Caine's 100 mm/24 h value as being insensitive to climatic differences, as well as runoff generation mechanisms, and called for the development of different thresholds for different parts of BC.

Outside BC, Crozier (1999) was one of the first to rigorously monitor and model antecedent moisture conditions and incorporate them into a 24-hour forecast model for landslide occurrence. Cannon et al. (2003 and 2008) considered post-wildfire debris flow in the western continental US and found that rainfall in excess of the 2-year, 60-minute intensity was sufficient to trigger debris flows from burned areas there.

Chatterton (1984) was an early developer of rainfall shutdown thresholds for specific regions of BC, in this case Vancouver Island and the South Coast region. He used two zones, designating them as the "dry zone" and "wet zone", with shutdown values of 55 mm/24 h for the dry zone and 100 mm/24 h for the wet zone. These criteria were adopted by the BC Ministry of Forests in 1994.

In the BC interior, there have been no large studies specifically intended to determine wet weather shutdown criteria, perhaps because the environmental variables which cause instability are more varied and heterogeneous than on the Coast or further south in the US. Published research and case studies which exist have usually concentrated on a subset of all events, either those within a particular region, those dating from a single storm, or those with a circumscribed causation. For instance, Tannant and Skermer (2013) reviewed historic information from a century of debris flows and dam failures in the Okanagan region. They concluded that both snowmelt and rainfall could trigger debris flows, and that a worryingly high proportion of the total events on record were caused by failures of dams, particularly old and poorly maintained earthen dams.

Jordan et al. (2003) and Jordan (2012, 2016) examined debris flow initiation after forest fires and found that after wildfires, debris flows were more likely to occur. He identified several factors, including hydrophobic soils, increased melt rates in burned areas, and loss of strength in steep channels if woody debris jams were burned, that contributed to the post-wildfire increases in debris flow frequency and magnitude.

There have been many studies and technical reports which examined either single landslides or debris flows, or small clusters of events, in the Interior. Examples include Jakob et al (2000) for the Hummingbird Creek debris flow at Mara Lake, Giles et al (2005) for the Stemwinder Creek debris flow, Nicol et al. (2013) for the Johnsons Landing/Gar Creek landslide and debris flow, and Turner (2017) for the Robinson Creek debris flow. Data from studies of this sort are important because they document site-specific antecedent conditions which can be subsequently analyzed statistically to attempt to determine more general threshold conditions.

An important factor highlighted by all of these studies is that longer-term antecedent moisture conditions, either as precipitation, snowmelt, or a combination of the two, can be more important than short-term weather conditions in causing instability. Factors correlated with the incidence of landslides and debris flows include:

- snowpack water equivalent, particularly peak snowpacks that equal or exceed previously recorded long-term maximum values;
- timing of snowmelt, especially when the spring melt of unusually deep snowpacks is delayed by cool spring weather that then changes to rapidly hot conditions;
- above-average or record high multi-week, monthly, or even seasonal total precipitation;
- intense short-term precipitation over an interval ranging from 30 minutes to 24 hours.

The snow water equivalent (SWE) and melt rate of snowpacks can be spatially and temporally variable over a period of several days, on different aspects, and within different stands in a single watershed, making the characterization of the precipitation equivalent generated by snowmelt more difficult. Values of 5 mm to 60 mm of water equivalent per day, and from 1 mm to 15 mm or more per hour, have been quoted in literature (Spittlehouse and Winkler, 2004; Nicol et al, 2013; Subramanian et al, 2018). This range of melt values overlaps with, and in some cases exceeds, precipitation intensities for comparable durations and low frequencies, such that the total snowmelt generated on a very warm day from a deep snowpack might be more equivalent precipitation than, for instance, the comparable 1-day 50-year rainfall.

Temperature can affect terrain stability even without the contributing effects of snowmelt. In continental cold climates such as the BC Interior, the ground typically freezes in late autumn or early winter to a characteristic depth, and remains frozen until spring. When the frozen ground melts, an event typically termed breakup, subsurface changes in pore water pressure and alterations in groundwater hydrology can occur as the melting front moves deeper into the subsurface. While the hydrologic changes caused by breakup typically occur at the same time as and are thus confounded by snowmelt, they can be observed in isolation in dry areas with minimal snowpack, or continue for a month or more after all snow has melted from an area.

Topography has been identified as a contributing factor in some landslides, debris flows and debris floods in the BC Interior. Specifically, so-called “gentle-over-steep” conditions, where an upland plateau or low-gradient headwater region lies above steeper slopes. These topographic conditions have been implicated where terrain instability occurs on the steep slopes after land cover or drainage pattern changes on the gentle slopes. A general theory of why gentle-over-steep topography results in increased instability has not been presented. Hydrologically, low-relief upland areas can lead to flow synchronization from large parts of the catchment during snowmelt, especially when compared to consistently steeper drainages over which temperature varies more widely with elevation. Likewise, geomorphic differences with sediment character and depth can be demarcated by prominent slope breaks. Finally, drainage diversions and increased runoff, particularly where road networks divert and concentrate runoff, can cause landslides either when the diverted runoff crosses a slope break, or when subsurface seepage to particular locales is augmented, although this factor is not specific to gentle-over-steep topography but applies equally to steep-over-steep topography.

Finally, some events confound casual attribution of causal relationships. Crookshanks (2019) presents a case study of a small debris flood at Morley Creek near Nelson. The debris flood occurred in August 2019, after an August 2017 fire. Two snowpacks had formed and melted, and two spring freshets had occurred, before the debris flood took place. Antecedent moisture conditions had been relatively warm and dry. The debris flood occurred after a rainstorm, but the rainstorm was neither particularly intense nor long-lasting, and no drainage diversions or infrastructure failures were highlighted as contributing factors. In short, a debris flood occurred, but the author could not definitively say why it occurred when it did or why it did not occur at another time when snowmelt or rainfall might have been greater. Events of this sort are the most challenging to address within a wet weather shutdown framework based on precipitation and snowmelt thresholds.

4.0 CURRENT BC INTERIOR ENVIRONMENTAL SHUTDOWN CRITERIA

Existing shutdown criteria in the BC Interior tend to favor simple, qualitative and subjective observational conditions rather than specific precipitation thresholds or other measured parameters. Additionally, they are often designed to cover a range of conditions, and have not been created to be specific to worker safety or to terrain stability. For instance, BC Timber Sales, Kootenay Business Area, currently uses a Wet Weather Operating Guide (2017) that is intended to protect worker safety, forest operations, and the environment, and to prevent damage to road systems. The operating guide includes a short list of indicators of terrain instability which should trigger immediate shutdown of operations, and a longer list of activities, recommended practices to minimize or mitigate the impact of those activities when operating in wet weather, and recommended shut down conditions by activity. For instance, one activity listed in the guide is trail construction, and the recommended shutdown conditions for this activity are if water is transporting sediment toward streams, if ruts of greater than 15 cm depth are being formed, if there is abundant hillslope runoff from spring freshet or prolonged heavy precipitation, or if sediment is flowing or parent material loses its ability to hold its shape. With the exception of the 15 cm depth criteria for ruts, all criteria presented are qualitative and subjective, i.e. “heavy” precipitation or “abundant” hillslope runoff, rather than a specified intensity or total amount.

BC Timber Sales’ Kamloops Business Area (2019) has a similar Wet Weather Operating Guide, which appears to be based on the same source material as the Kootenay Business Area’s guide, but which includes additional material in a preamble on the purpose of the guide. This purpose section indicates that the guide can be used where a terrain stability assessment or terrain classification have indicated that unstable terrain exists or where slopes are in excess of 60% gradient as well as where site plans have indicated that sensitive soils exist. The section concludes with a general statement:

> “*Discontinu[ing] logging and road building activities during particularly intense rainstorms can reduce the risk of landslide or erosion events. If the total amount of rainfall over a specific time period is excessive, the operations should be halted to avoid environmental damage.*”

Interfor (2015) produced a Log Hauling Shut-Down Procedures document. As the title suggests, it is intended to guide the shutdown of log hauling operations when weather conditions warrant. The criteria include early or late-season snow events while the temperature is in the range of -2 °C to 2 °C, freezing rain, or more than 4 cm to 6 cm of fresh wet snow where a grader or sand truck cannot keep the road maintained, as well as high winds with risk of blowdown, and rain events "after a period of dry on steep ground".

Tolko's Wood Procurement Program Best Management Practices (2019) includes the following statement under the heading of Soil Conservation:

> "*Weather conditions can be a major factor in soil disturbance. Operations should avoid conditions that create excessive rutting or compaction. Plan operations with soil disturbance in mind. Weather conditions and soil disturbance should be assessed and consideration given to curtailing or stopping activities causing soil disturbance when soils are too wet to support equipment. For example, in the BC Interior and prairies, consider winter harvesting on wet ground to better support equipment. With different soil types, and phases of harvesting, it may be possible to carry out some operations in wet weather without causing excessive soil disturbance. Appropriate equipment should be used to minimize soil disturbance.*"

An additional factor applicable throughout the BC Interior, alluded to in the BCTS Kamloops guidelines, is the Seasonal Load Restrictions enforced by the Ministry of Transportation and Infrastructure (MoTI) during the spring breakup. When MoTI designates load restrictions, hauling on highways or other public roads may be severely curtailed, which has the effect of restricting or shutting down some forestry operations during the breakup period. Log hauling and transport of heavy equipment is restricted, but other activities, such as layout and tree planting, which typically use quads or pickup trucks, are not similarly restricted.

MoTI uses its own shutdown criteria for certain projects. On the Five Mile landslide near Fountain, northeast of Lillooet, Highways contractors are stabilizing Highway 99 where it crosses a deep-seated and slow moving landslide. BC MOTI previously used a combined shutdown and slope movement monitoring criterion of 10 mm of rain/24 hours for this project (S. Gaib, p. comm, 2019) but have since switched to slope monitoring alone.

4.1 Effectiveness of Existing Shutdown Criteria

The existing shutdown criteria in the BC Interior are simple and mostly depend on subjective interpretation of qualitative parameters. A few quantitative measures are included, such as rut depth or the temperature range under which to stop log hauling, but for most parameters, judging whether precipitation or runoff is intense, abundant or excessive is a personal call. Accordingly, two similarly experienced people might make differing judgements about whether to shut down operations while experiencing the same conditions.

In addition, because intervals or thresholds are not quantitative, there is little guidance from the existing guidelines on when operations can resume after being shut down. Rather, as for determining if shut down is warranted, the decision on when to resume once or if hazardous or inoperable conditions cease is subjective and personal.

Despite the subjective and qualitative nature of the existing guidelines, there have been few injuries or fatalities within the forest industry over the past few decades as a result of landslides or slope instability. Most recorded fatalities and injuries in the BC Interior from these processes result when landslides, debris flows, or debris floods reach transportation corridors or private property in valley bottoms.

Case studies of such events can determine whether the shutdown criteria that were in place were followed or not, but the total number of events is too small to permit a statistically significant analysis of the comparative effectiveness of different shutdown criteria. Therefore, the design and implementation of new shutdown criteria cannot be entirely evidence-based, because the existing evidence is inadequate; they must incorporate professional knowledge and experience, as well as discussions of acceptable risk levels.

There are two measures of effectiveness. When no shutdown is recommended and landslides do not happen, and when shutdown is recommended and landslides happen, the shutdown guidelines are functioning as designed. The possibility of landslides occurring when shutdown is not recommended, as discussed above, is an obvious potential failure of the shutdown guidelines, but occurs too rarely to be successfully analyzed statistically to determine the comparative effectiveness of different shutdown thresholds.

The second case to be considered is the failure of shutdown guidelines that happens when shutdown is recommended but no landslides occur. This incurs an economic cost that must be balanced against the decrease in safety incurred by less conservative shutdown guidelines. It also affects the participation of workers affected by the guidelines, since if people are stopped from work frequently without obviously unsafe events occurring, they may come to distrust the guidelines, and then ignore them when dangerous conditions occur that truly do warrant shutdown.

Although the sample size for deaths, injuries, and damage to equipment caused by lenient shutdown criteria is very small and thus difficult to analyze, it is relatively easy to evaluate the potential economic cost of any recommended shutdown criterion by comparing it to (measured or modelled) rainfall intensity or expected snowmelt and determining the return period of the shutdown criterion, i.e. a shutdown criterion that results in work being stopped, on average, for four days per year will be twice as expensive as one that results in work being shut down for only two days per year on average.

5.0 EVALUATION OF EXISTING SHUTDOWN CRITERIA

Shutdown criteria have been used on the Coast since the 1980s, and several different versions have been used by municipal and provincial governments and private forest companies over the years. The user experience gained from using these shutdown criteria can inform the design of new shutdown criteria for other areas, including the BC Interior.

An underappreciated problem of shutdown criteria is design, specifically in the creation of criteria that work for the intended user. Shutdown criteria in BC are primarily used by forestry workers, and to be effective, they must therefore work for the typical job site, reading level, and with the equipment typically available for forest workers.

A related problem is that of over precision. The environment is inherently variable, and this applies to typical job sites or work sites as well. Some past shutdown criteria used on the BC Coast made fine distinctions between closely adjacent locations, so that one cutblock might shut down at 38 mm of precipitation over 24 hours while a second cutblock, 300 m away, might shut down at 44 mm. It is hard to justify such a narrow distinction on scientific grounds when environmental variability and the inherent error in measurements are considered together; a single value of 40 mm/24 h would probably have been sufficient to apply to both areas, especially if the shutdown was determined from a rainfall gauge which measured precipitation at a third location equidistant from the two cutblocks.

Shutdown criteria must work for the users who will be affected by them. The use of a rain gauge and thermometer on job sites, at least on the BC Coast, is common. Measurement of parameters beyond these, such as wind speed or the amount of snowmelt, can prove difficult for workers, particularly if it requires instrumentation such as atmometers, weather stations, or snow courses which in turn require trained technicians to read and interpret. Likewise, factors such as distance to remote areas, measurement uncertainty and error, the decentralized nature of forest tenure, and communications difficulties can make it difficult or impossible for a central authority to determine when and where to shut down work and then communicate these decisions to workers in the field.

To be effective when used in the field, the interval between measurements necessary to determine whether work should shut down or not must neither be too long nor too short. If it is too long, workers may forget to do it because it is infrequent, or miss detecting hazardous conditions. If it is too short, work is disrupted because of the need to make frequent measurements, or an additional cost is incurred because of the need for an additional worker to make and record measurements. Recording measurements should also be as simple as possible, and ideally determining whether to shut down or not can be simply determined from past and present measurements, either directly or by comparing a summed value to a table. Experience has shown that if shutdown needs to be determined from a combination of complex factors recorded over time, or if the answer must be derived from a graph plotted by users, or if it involves making a discrimination which only a trained professional can make, it will likely not be determined accurately.

It is important to distinguish between environmental shutdown criteria designed for worker safety and environmental shutdown criteria designed for environmental management. From discussion with BCTS staff, shutdown criteria intended to manage worker safety have sometimes been used to manage for other values in the absence of more specific criteria. Typically, shutdown criteria designed to manage environmental values, such as to protect water quality in community watersheds, are much more stringent than criteria designed to protect worker safety, because safe work is still possible under environmental conditions where water quality may be adversely affected. Shutdown criteria for worker safety may be defined broadly (by climatic region) whereas shutdown criteria for environmental values would typically be best defined locally, depending on the environmental value(s) to be managed, through means such as watershed assessments or terrain stability and sedimentation hazard assessments.

Finally, the decision on when it is safe to resume work is as important as the decision to stop work. If work is resumed too soon, workers are placed at risk; if it is too slow, they are unnecessarily idled. If the determination of whether to resume work is always defaulted to professional judgement, it is likely that in some cases workers will be unnecessarily idled as well, if only because qualified professionals are in short supply and hence there will be unavoidable delay until one arrives on site. Including explicit guidelines on the return to work is therefore desirable for any guideline that prescribes work stoppage.

6.0 CHARACTERIZATION OF INTERIOR CLIMATE

Climate across the BC Interior ranges from very dry to wet, across terrain that includes plateaus, valley bottoms, uplands and high mountains. Characterizing this terrain in a consistent way is necessary in order to develop a homogenous set of shutdown criteria that are specific to the Interior's climatic conditions.

Thankfully, new tools are available that use global and local climate models and the input from long-term climate stations to predict climatic parameters at ungauged locations across British Columbia. These new tools have broadened our ability to understand how the climate varies across the landscape and changes with elevation. I used two of these tools, ClimateBC (Wang et al., 2016) and IDF_CC 4.0 (Simonovic et al., 2018) to evaluate climate parameters across the BC Interior. I selected 25 points that represented a wide range of annual precipitation, elevation, and distribution across the region, from Ashcroft to Elkford and from valley bottom to high mountain summits. For each location I predicted mean annual precipitation, precipitation as snow water equivalent, mean annual rainfall, and the expected 1-hour, 12-hour, and 24-hour precipitation intensities for the 2-year recurrence interval (Appendix 1, Figures 1 and 2).

The results show that with respect to total precipitation, mean annual rainfall does not vary much across the region, while mean annual snowfall does (Figure 1, Appendix 1). That is, most areas have similar rainfall, and it is the amount of snowfall (and the length of the snowfall season) that varies and that determines total precipitation. As a corollary, though, for almost all locations that receive less than about 1000 mm total annual precipitation, there is more rain than snow. Areas receiving more than about 1100 mm of mean annual precipitation typically have more snow than rain. Finally, the range of 1000 mm to 1100 mm of mean annual precipitation is typically equivalent to approximately equal amounts of rain and snow.

Conversely there is no correlation between mean annual precipitation and precipitation intensity over any calculated duration, but there is a weak correlation between mean annual rainfall (summer precipitation) and longer-duration (12 and 24 hour) precipitation intensity; wetter areas have higher 12-hour and 24-hour precipitation intensities than dry areas do. There is a much weaker trend for the 60-minute/1-hour precipitation intensity; almost all areas have a 1-hour precipitation intensity of between 8 mm and 10 mm (Figure 2 Appendix 1).

This climate information has direct relevance to shutdown criteria because it illuminates the relationship between precipitation intensity and snowmelt. In dry or very dry areas, there is very little snow, and annual rainfall exceeds annual snowfall. Because there is very little snow, it usually melts early in the year (March or April) before high temperatures typically occur, and the rate of snowmelt is often slow. Consequently, the intensity of extreme precipitation is typically greater than the maximum rate of snowmelt experienced in a typical year, and so it is intense rainfall that results in the wettest events.

In wet areas, by contrast, there is a lot of snow, and it persists much later into the year, and some is typically still present when very warm temperatures can occur (late April, May, or June). The snowmelt rate under these conditions can exceed the maximum rainfall intensities experienced over the same time periods (Spittlehouse and Winkler, 2004; Nicol et al, 2013; Subramanian et al, 2018). Consequently, it is the timing and intensity of snowmelt and not of rainfall that results in the wettest events of the year in these areas.

These predictions are point-specific and should be interpreted in that light. Watersheds are areas which contain a range of elevations and over which precipitation continuously varies. Intense convective precipitation has a discrete scale, with individual cells often only about 1 km^2 in area. Therefore, when interpreting these results to watershed scale, the size of the watershed is important, as is its elevation. A 1 km^2 watershed in a valley bottom in the BC Interior, especially in the Thompson-Okanagan area, is likely to have low total annual precipitation, annual rainfall in excess of annual snowfall, and as a result the largest peak flows it experiences will result from summer thunderstorms and not spring snowmelt. In large watersheds which drain from high alpine areas, conversely, it is likely that snowmelt will drive peak flows not only because snowfall exceeds rainfall, but because the scale of the watershed means that intense rainfall does not affect the whole watershed at once (Beckers et al, 2002). Landslides and debris flows are not always peak flow-driven, but the hydrometeorologic thresholds which trigger these events are also the events which cause peak flows, floods and debris floods. The difference in timing is largely due to the difference in scale together with the differences in surface and subsurface flow paths and flow rates.

7.0 RECOMMENDED SHUTDOWN CRITERIA FOR BC INTERIOR

The southern Interior of BC is a large and heterogenous region with notable differences in climate, annual precipitation, elevation range, hydrology, bedrock geology, and surficial materials. It includes both desert areas and mountainous parts of the Interior Wet Belt where precipitation equals that experienced on some parts of the coastal BC. Accordingly, the harmonized criteria must be capable of predicting when shutdown of operations is warranted over a wide range of environmental conditions from dry to wet, and over a similarly wide range of surficial geologies, flood and landslide generation processes, timings of runoff, and past histories of disturbance.

7.1 When to Use Shutdown Criteria

Workers are exposed to geotechnical hazards not only at the work site but also along access routes that reach the work site. Accordingly, shutdown criteria must apply to not only work sites such as cutblocks and roads under construction, but also roads used for access to and from these work sites.

Environment Canada provides forecasts and measurements of rainfall of varying accuracy for all of the areas of the southern Interior. Where forecasts and measurements do not accurately reflect conditions at the work site, they typically underestimate, rather than overestimate, actual rainfall. Therefore, workers should check forecasts and reported rainfall totals before travelling to the work site. If predicted or recorded rainfall for the day exceeds the listed shutdown thresholds, it is likely unsafe to travel to the work site, and there is no need to expose workers to hazards while checking the rain gauge at the work site.

Otherwise, shutdown criteria should apply when work sites or access routes are located on, downslope of, or are exposed to landslide-prone terrain. "Landslide prone terrain" includes, but is not limited to:

- areas with greater than 60% slope gradients,
- areas mapped as unstable or potentially unstable (U or P) on reconnaissance terrain stability mapping,
- areas mapped as Class III, IV, IVR, or V on detailed terrain stability mapping,
- areas identified as being subject to slope instability, or where landslides would deposit, by qualified professionals in terrain stability field assessments,
- gullies or alluvial fans, or
- areas affected by past landslides.

Exceptions may be made where the nearest landslide-prone terrain is more than 300 m upslope of the work site or access route and the intervening terrain is both low-gradient (i.e. with slope gradients of 30% or less throughout) and not a fan.

7.2 Basic Shutdown Criteria by Zone

Table 1 provides the recommended shutdown criteria based on rainfall for four climatic zones plus one "identified unstable conditions" zone, over four time intervals. Climatic zones should be determined for a specific location from an online climate model such as ClimateBC (Wang et al, 2016). It is relatively simple for foresters, geoscientists, or other qualified professionals to use such models and specify the annual precipitation in a terrain report or project particulars for a proposed cutblock or road and thus to identify the appropriate zone for workers to use when evaluating shutdown criteria.

Table 1: Proposed Shutdown Criteria by Zone,

Zone	Zone (annual precipitation)	Time Period			
		One hour	At start of or before end of shift (12-hr)	24-hr	48-hr
1	Very wet (1500 mm to 3000 mm)	n/a	28 mm	35 mm	60 mm
2	Wet (1100 mm to 1500 mm)	n/a	25 mm	30 mm	50 mm
3	Average (600 mm to 1100 mm)	10 mm	22 mm	25 mm	40 mm
4	Dry (100 mm to 600 mm)	8 mm	18 mm	20 mm	30 mm
5	Identified Unstable Conditions	6 mm	10 mm	15 mm	20 mm

Table 1 assumes that rainfall will be measured in a gauge at the work site. It is expected that in some forestry settings, there may be a considerable elevation range between the elevation of the rainfall gauge and the highest elevation at which work is taking place, and that more rainfall may occur at higher elevations than is measured at the gauge; the shutdown criteria incorporate this assumption.

"Identified unstable conditions" refers to conditions where a qualified professional has identified and documented conditions at or upslope of the work site which require special precautions for safe work beyond those which are normally applicable, but has not provided site-specific shutdown criteria which can be used in place of these general criteria. Identified unstable conditions can occur in any precipitation zone. This category might be used, for instance, to guide operations when attempting to determine if it is safe to rebuild a road across the deposit of a recent landslide. Examples of items from terrain stability field assessment reports that might indicate "identified unstable conditions" include old, undeactivated roads with tension cracks and drainage diversions upslope of a work site, landslide scars upslope of a work site, roads which cross gullies identified as experiencing debris flows, or terrain identified as having high or very high terrain stability hazard upslope of a work site. It is also appropriate to use this category when an area has experienced a forest fire within the last three years. If a qualified professional provides site-specific shutdown criteria for a particular unstable location, those should be used instead of these general criteria.

7.3 Snowmelt

It is possible to convert air temperatures into equivalent precipitation values from expected snowmelt. Typically, however, accurate models of this process must be calibrated to specific drainage basins or include extra terms for aspect, radiative forcing and wind speed. Those are probably beyond the scope of wet weather shutdown guidelines, and also, the accuracy is not necessarily needed. Although using temperature alone is less accurate, the accuracy suffices for the purpose because it is possible to incorporate the uncertainty and error using conservative (i.e. overestimated) values for the expected snowmelt for a given temperature (Table 2). Values not present on the table should be interpolated from the listed values.

Values in Table 2 have been computed and interpolated from established procedures for evaluating snowmelt from temperature including Savabi et al (1995), USDA (2004), Spittlehouse and Winkler (2004), Jennings and Jones (2015), Subramanian et al. (2018) and Massmann (2019).

Table 2 can be used to estimate the amount of water (mm, precipitation equivalent) based on air temperature. To estimate hourly melt rate, use an hourly temperature. To estimate 12-hour or 24-hour melt, use mean daily temperature. For instance, if a site has a mean daily temperature of 14 °C, but a peak afternoon temperature of 20 °C, the expected peak 1-hour melt rate will be 4 mm/hour, but the values will be 29 mm and 43 mm for the 12-hour and 24-hour intervals, respectively. The 12-hour interval here is expected to be the warmest (approximate daylight) hours; the expected melt at night will be less (14 mm) such that the daytime melt plus the additional night time melt equal the 24-hour melt.

The expected melt can be compared to the shutdown criteria in Table 1 to determine if shutdown should occur. In the example above, the expected 12-hour and 24-hour melt exceeds the 12-hour and 24-hour shutdown criteria for all zones, so work should shut down.

Table 2: Estimated Snowmelt by Air Temperature

Air Temperature (°C)	Expected Melt Rate (mm)		
	Peak Hourly	12-Hour Total (Day)	24-Hour Total (Day+Night)
1	1	4	6
2		6	8
3		8	11
4		10	14
5		11	17
6		13	20
7		15	23
8	2	17	26
9		19	29
10		21	32
11		23	35
12		25	37
13	3	27	40
14		29	43
15		31	46
16		33	49
17		35	52
18	4	37	55
19		39	58
20		41	61
21		43	64
22		44	66
23	5	46	69
24		48	72
25		50	75
26		52	78
27		54	81
28		56	84
29	6	58	87
30		60	90

The snowmelt calculation expects that the snowpack will have a late-spring density in the range of 0.35 to 0.4, such that each 10 mm of melt water lost will reduce snowpack depth by 25 mm to 30 mm. The measured depth of snow can then be used as an upper limit to the amount of melt that can occur. If there is only one foot (300 mm) of snow on the ground, that represents about 114 mm of water equivalent, which would therefore take about 3 days to completely melt at an average air temperature of 14 °C. No minimum depth of snow is specified, but it will be seen from Table 2 that small or trace amounts of snow cannot generate enough water, even at hourly rates, to trigger any shutdowns before completely melting.

The amount of expected snowmelt can be directly added to the amount of measured precipitation to determine if shutdown criteria are exceeded. If working in the dry zone, the shutdown criteria is 8 mm/hr. If 5 mm of rain falls in one hour, there is snow on the ground, and the air temperature is 14 °C, the total amount of water per hour (rain plus snow) is 5 mm of rainfall plus 3 mm of snowmelt, which equals 8 mm, so work should shut down.

7.4 Modifiers to Shutdown Criteria

Numerous factors other than direct rainfall can contribute to slope instability, including high winds, blocked drainage structures or diverted drainage upslope, long-term antecedent precipitation, earthquakes, and other less probable events. Unlike rainfall, these factors can be difficult for on-site workers to measure accurately; factors like wind speed are even less amenable to simple measurement by workers than are snowpack and snow melt. The variability of these factors with elevation can also be greater than the variability of rainfall with elevation.

To account for these factors without requiring multiple difficult and potentially inaccurate calculations, a simpler system is proposed. Potential additional risk factors beyond simple rainfall totals are listed below. The presence of one or more of these additional risk factors cause the zone number used to determine the shutdown criteria to change. Each risk factor present shifts the zone number up by one. For instance, a project is located in Zone 2 which has a 24-hr threshold of 30 mm. A storm brings 20 mm of rainfall in 24 hours, accompanied by high winds of 80 km/h. Zone 2 is therefore shifted to Zone 3 to account for the high winds; 20 mm is still less than the Zone 3 24-hour shutdown criteria of 27 mm, so work can continue.

The additional risk factors beyond rainfall totals are:

- High winds (wind speed reported or predicted >60 km/h, or visibly or audibly breaking crowns or branches, or causing windthrow) at job site;
- Very wet conditions (defined as any period of 21 days or longer with precipitation or snowmelt recorded on every day). Periods longer than 21 days do not increase the very wet conditions hazard further;
- Visibly high stream flow (ditches full and overflowing onto roads, culverts discharging at capacity, culverts blocked by debris flow and diverting water to adjacent streams, floodwater present on adjacent highways, River Forecast Centre high streamflow or flood advisories or warnings for the area, etc.)

If the presence of additional risk factors increases the zone beyond Zone 5, i.e. beyond the "identified unstable conditions" zone, work should shut down regardless of whether or not the rainfall shutdown value has been exceeded, and should remain shut down until the additional risk factors are no longer present.

8.0 OTHER SHUTDOWN CRITERIA

In addition to shutdowns resulting from the exceedance of rainfall criteria, workers and supervisors should remain aware of other indicators of geotechnical instability. These can include, but are not limited to:

- pulses of sediment-laden (turbid) water in streams, especially in gullies,
- streams suddenly drying up when conditions are otherwise wet,
- constant small rock falls,
- cutslope slumps that block ditches and/or roads,
- tension cracks appearing in road fills or slopes,
- recent avalanches, landslides, or debris flows or their deposits observed that were not present during the last shift,
- anchor stumps pulling out of wet ground during cable yarding,
- diverted streams with flow appearing in new stream courses that were previously dry.

If any of these indicators of instability are observed, work should shut down until a qualified professional can be brought in to determine if it is safe for work to proceed.

These shutdown criteria apply to landslides and debris flows that form the predominant geotechnical hazards to workers. They are most likely to anticipate small landslides of the sort that are typically associated with forestry activity. Very large bedrock landslides, on the scale of the Hope Slide or Frank Slide, respond to different and less predictable environmental criteria. These shutdown guidelines may not protect workers from such very large events, but these events are also very rare and so the corresponding risk associated with them is also low.

Snow avalanches pose seasonal hazards to workers and exposure to snow avalanches should be managed by qualified professional avalanche technicians.

Rockfalls often pose an additional hazard to workers. Many rockfalls occur under the same environmental conditions that cause landslides and debris flows. In addition, freeze-thaw cycling, especially on clear days during winter with warm days and cold nights, can cause rockfall. If rockfall is an identified hazard that can affect a work site, workers should be aware of the potential for freeze-thaw conditions to trigger rockfall and take appropriate precautions. In most cases, freeze-thaw generated rockfall does not occur at scales necessitating complete shut down of work, and can be managed to reduce risk to tolerable levels by reducing worker exposure to areas in which rock fall is likely to occur or deposit, such as at the base of bluffs or road cuts.

8.1 Resumption of Work after Shut Down

Once shutdown criteria have been exceeded, work should remain shut down for at least 24 hours after the hazardous conditions end. In the case of 48-hour rainfall criteria being exceeded, work should remain shut down for at least two days (48 hours) after shutdown criteria have been exceeded. If workers and supervisors believe it is safe for work to resume before the recommended 24- or 48-hour period is over, they should consult a qualified professional to confirm and document this before resuming work.

9.0 EXPECTED SHUTDOWN FREQUENCY

The shutdown criteria in Table 1 are based around an expected shutdown frequency of about one day every two years. That is, workers can expect to be shut down for about one day every other year, on average, while using these criteria, with the shutdown more frequent, perhaps up to one week per year or more, while working in the most hazardous conditions, in identified unstable terrain. This frequency has been deliberately chosen. More frequent events, which are exceeded several times per year on average, do not typically result in hazardous conditions. Likewise, there is not much benefit to using a rarer event, such as the one-in-five or one-in-ten year event, to trigger shutdown. The difference between using the 1-in-2 year event (which shuts down work five days in ten years, on average) and the one-in-10 year event (which shuts down work for one day in ten years) is four days out of ten years, or significantly less than one day per year; there is just not much significant time saved on an annual basis for using an event that is less frequent than once in two years.

10.0 LIMITATIONS

WorkSafeBC Section 20.78 (Excavations) requires written instructions by a qualified professional that specifies the influence of changing weather conditions on the stability of an excavation. This procedure does not waive or take precedence over the requirements of WorkSafeBC Section 20.78.

The recommendations provided in this report are based on observations made by Statlu and are supported by information Statlu gathered. Observations are inherently imprecise. Conditions other than those indicated above may exist. If such conditions are observed or if additional information becomes available, Statlu should be contacted so that this report may be reviewed and amended accordingly.

This report was prepared considering circumstances applying specifically to the client. It is intended only for internal use by the client for the purposes for which it was commissioned and for use by government agencies regulating the specific activities to which it pertains. It is not reasonable for other parties to rely on the observations or conclusions contained herein.

Statlu prepared the report in a manner consistent with current provincial standards and on par or better than the level of care normally exercised by Professional Geoscientists currently practicing in the area under similar conditions and budgetary constraints. Statlu offers no other warranties, either expressed or implied.

11.0 CLOSURE

Please contact me should you have any questions or if you require further clarification.

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2021-04-29

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APPENDIX 1: ANALYSIS OF PRECIPITATION, RAINFALL AND SNOWFALL ACROSS THE SOUTHERN INTERIOR OF BC AND FIGURES

Location	ClimateBC Annual Precipitation (mm)	Precipitation as Snow (cm)	Rainfall (mm)	IDF_CC 1 hour 2 Year Precipitation (mm)	IDF_CC 12 hour 2 Year Precipitation (mm)	IDF_CC 24 hour 2 Year Precipitation (mm)
Ashcroft	257	31	226	6	22	24
Kelowna	324	32	292	8	18	21
Logan Lake	346	82	264	8	20	22
Cranbrook	409	131	278	9	21	25
Golden	462	215	247	8	21	27
Pass Creek	509	90	419	10	24	28
Elkford	550	305	245	8	21	26
Coalmont	593	186	407	8	21	26
Elkhart Lake	674	321	353	9	18	19
Procter Lake	724	275	449	11	29	38
Seymour Arm	745	123	622	8	21	29
Nakusp	813	116	697	10	27	32
Rossland	878	242	636	10	24	29
3 Valley Gap	881	194	687	9	27	39
Retallack	1052	331	721	9	23	28
Mica Dam	1082	477	605	8	24	32
Big White	1204	827	377	9	22	24
Jumbo Glacier	1269	813	456	9	22	27
Rogers Pass	1285	668	617	8	21	27
Whatshan Peak	1382	896	486	10	26	31
Stagleap	1635	956	679	10	23	29
Pierrway Icefield	1941	1402	539	9	23	30
White Rabbit Cave	2057	1351	706	8	23	31
Copperstain Mtn	2248	1793	455	8	21	27
Iconoclast Mtn	2685	2334	351	8	21	28

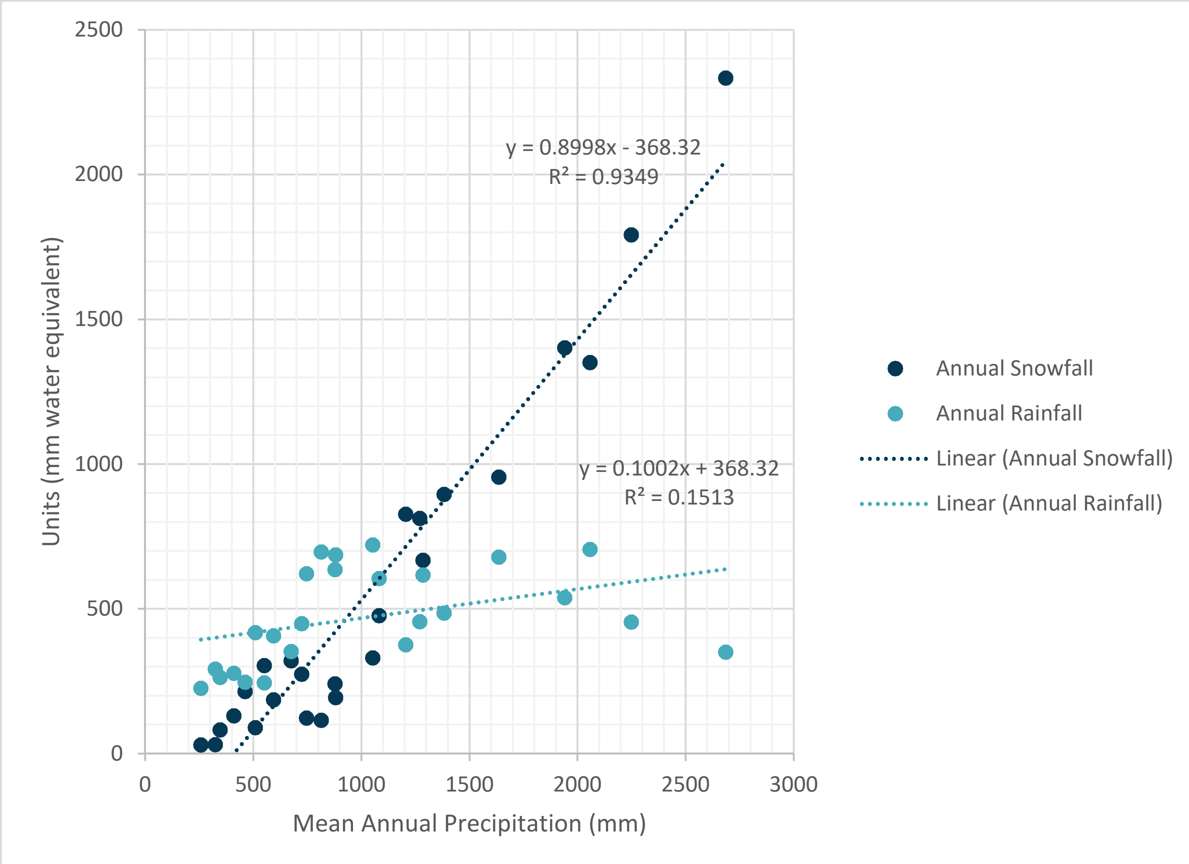

Figure 1: Mean Annual Precipitation (Rainfall and Snowfall Components as Function of Total Precipitation), Southern Interior BC

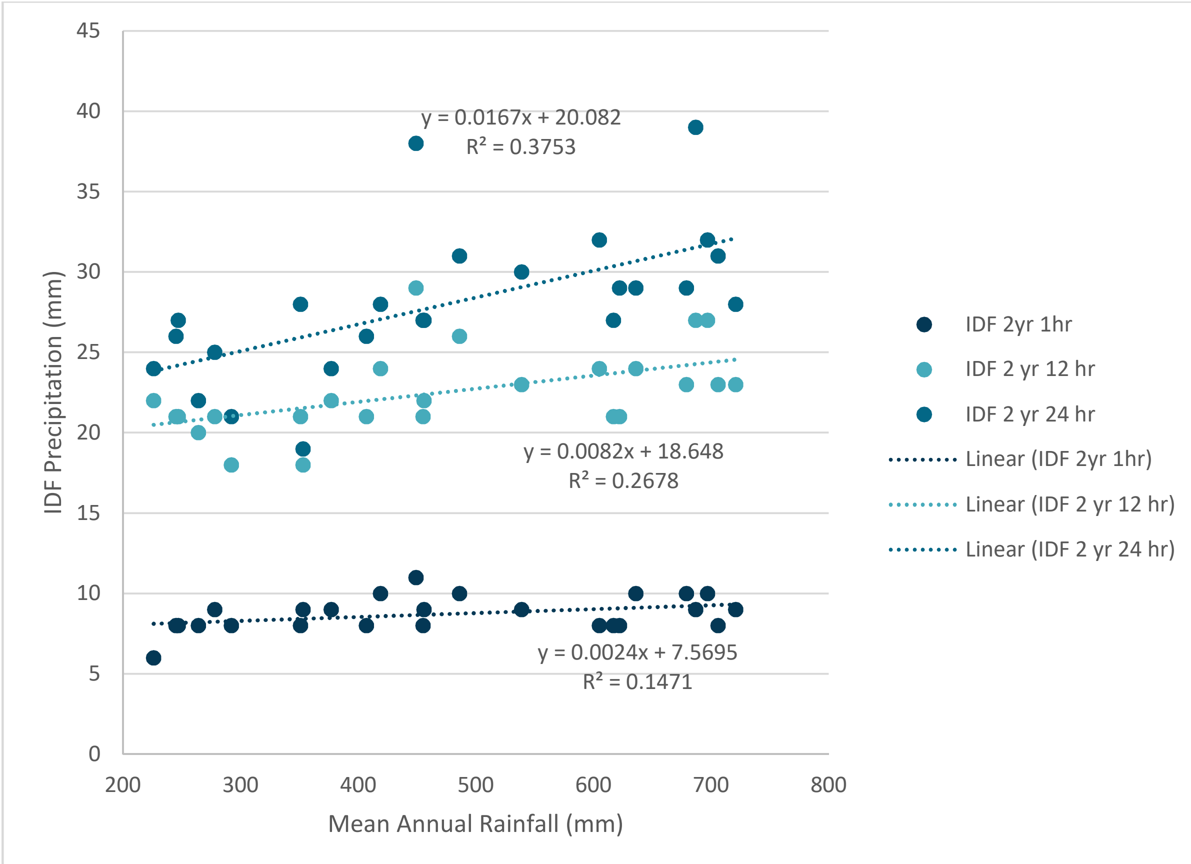

Figure 2: Intensity-Duration-Frequency of Precipitation as Function of Mean Annual Rainfall, Southern Interior BC