Hydrologic effects of mountain pine beetle infestation and salvage-harvesting operations

John Rex and Stéphane Dubé

Mountain Pine Beetle working paper 2009-05

Ministry of Forests and Range
5th Floor, 1011-4th Avenue
Prince George, BC V2L 3H9

MPBI Project # 8.26

Natural Resources Canada
Canadian Forest Service
Pacific Forestry Centre
506 West Burnside Road
Victoria BC V8Z 1M5

2009

Library and Archives Canada Cataloguing in Publication

Rex, John F
Hydrologic effects of mountain pine beetle infestation and salvage
harvesting operations [electronic resource] / John Rex and Stéphane Dubé.

(Mountain pine beetle working paper ; 2009-05)
"MPBI Project # 8.26".
Includes bibliographical references.
Type of computer file: Electronic monograph in PDF format.
Issued also in printed form.
Includes abstract in French.
ISBN 978-1-100-13141-2
Cat. no.: Fo143-3/2009-5E-PDF

1. Soil moisture--British Columbia--Vanderhoof Region. 2. Water balance
(Hydrology)--British Columbia--Vanderhoof Region. 3. Forest soils--British
Columbia--Vanderhoof Region. 4. Forest hydrology--British
Columbia--Vanderhoof Region. 5. Watershed hydrology--British
Columbia--Vanderhoof Region. 6. Mountain pine beetle--British
Columbia--Vanderhoof Region. I. Dubé, Stéphane, 1968- II. Pacific Forestry Centre III. Title. IV. Series: Mountain Pine Beetle Initiative working paper (Online) 2009-05

SB945 M78 R49 2009 631.4'32 C2009-980159-0

Abstract

The mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemic is changing British Columbia's forests and watersheds at the landscape scale. Watersheds with pine-leading stands may experience changes in their water balance once the pines die. Forestry stakeholders in the Vanderhoof Forest District have reported an increase in groundwater storage. They report a replacement of summer ground (dry, firm soil) with winter ground (wetter, less firm soil), upon which operation of forestry equipment is difficult or impossible before freeze-up. This project was developed to identify a set of risk indicators to predict the risk of summer-ground loss at the watershed level within the Vanderhoof Forest District and others. Risk indicators were selected from available GIS information, aerial photographs, and local knowledge. To make these indicators operationally applicable in forest planning, general information such as watershed aspect, slope, soil type, and others were used. Indicators were selected during an iterative process that included model refinement, prediction, and field verification over a two-year period and a *post-hoc* assessment of field information to select the indicators that explain most data variability. The most effective indicators for predicting the risk of wet-ground areas at the watershed level were found to be lodgepole pine content, understorey, drainage density, sensitive soils, and the topographic index, all of whose values are available from provincial databases.

Keywords: Mountain pine beetle, soil hydrology, risk indicators, risk assessment, water balance

Résumé

L'infestation de dendroctone du pin ponderosa (*Dendroctonus ponderosae* Hopkins) est en train de modifier tout le paysage des forêts et bassins versants de la Colombie-Britannique. Le bilan hydrique des bassins versants où dominent les peuplements de pins peut subir des changements lorsque les pins meurent. Les intervenants du secteur de la foresterie dans le district forestier de Vanderhoof ont fait part d'une augmentation des quantités d'eaux souterraines. Ils indiquent que le terrain estival (sol ferme et sec) est remplacé par un terrain hivernal (sol plus humide et moins ferme), sur lequel il est difficile, voire impossible, d'utiliser le matériel de foresterie avant le gel. Le projet a été élaboré pour déterminer un ensemble d'indicateurs de risques, afin de prédire le risque de perte de terrain estival à l'échelle du bassin versant, dans le district forestier de Vanderhoof et d'autres. Les indicateurs de risques ont été sélectionnés à partir de renseignements donnés par le SIG, de photographies aériennes et de connaissances locales. Pour que ces indicateurs soient exploitables dans la planification forestière, des renseignements généraux ont été utilisés, tels que l'aspect du bassin versant, la pente, le type de sol et autres. Les indicateurs ont été sélectionnés au cours d'un processus itératif comprenant une amélioration du modèle, des prédictions, une vérification sur le terrain sur une période de deux ans et une évaluation ultérieure de l'information recueillie sur le terrain, afin de choisir les indicateurs qui expliquent la plupart des variations de données. L'étude a permis de démontrer que l'abondance du pin lodgepole, la régénération pré-établie, la densité du réseau hydrographique, les sols fragiles à texture fine et un indice de pente étaient les meilleurs indicateurs pour prédir le risque de perte de terrain estival pour les opérations forestières. Ces indicateurs sont disponibles à partir de bases de données provinciales.

Mots clés: dendroctone du pin ponderosa, hydrologie du sol, indicateurs de risques, évaluation des risques, bilan hydrique

Table of Contents

List of Tables

List of Figures

Glossary of acronyms and abbreviations

ANOVA – analysis of variance
BEC – biogeoclimatic ecosystem classification
CV – coefficient of variation
Db – bulk density
GLM – general linear model
HC – hydraulic conductivity
Ksat – saturated hydraulic conductivity
Kfs – field-saturated hydraulic conductivity
MPB – mountain pine beetle
MSC – Meteorological Services Canada
PCA – principle components analysis
PEM2 – predictive ecosystem model 2
VFD – Vanderhoof Forest District
SFH – simplified falling-head technique
SWSC – soil water storage capacity
SBS mc2 – Sub-Boreal Spruce Babine moist-cold
SBS mc3 – Sub-Boreal Spruce Kluskus moist-cold
SBS dw2 - Sub-Boreal Spruce Blackwater dry-warm
ESSF mv1 – Engelmann Spruce–Subalpine Fir Nechako moist-very cold
SBS dw3 – Sub-Boreal Spruce Stuart dry-warm
SBS dk – Sub-Boreal Spruce dry-cool

1 Introduction

The mountain pine beetle (MPB) epidemic presents a new challenge to forest managers because of its large spatial extent and its unknown effect on both the ecological condition of British Columbia's watersheds and the economic value of resources drawn from them. In response to the infestation, the allowable annual cut was increased in the most heavily infested areas to recover the economic value of attacked pine stands and to expedite the regeneration of new forests in those areas. The Vanderhoof Forest District (VFD) received the annual allowable cut uplift, but salvage operators often reported difficulties with salvage operations due to a loss in summer ground between 2003 and 2005. That is, during those harvest years, they report encountering wet soils that made equipment operation difficult or impossible where they had expected dry soils capable of supporting heavy equipment.

Stakeholder observations were considered a management concern because the landscape-scale change they identified signalled a possible change in water balance and subsequent ecology of affected areas, and they may make access to the dead timber more expensive for the licensee. This project was developed to identify a set of risk indicators to predict watersheds that have higher potential for wet ground areas subsequent to the MPB infestation of lodgepole pine stands. This project addressed the following questions:

- Are there watersheds that are prone to losing summer ground?
- What biological and physical indicators best describe a watershed at risk of losing summer ground?

1.1 Hydrology overview

Observations about the conversion of summer to winter ground in the VFD can be explained using the water balance approach, which is a formula often used to conceptualize water movement (Ward and Trimble 2004). Its simplified general form is:

$$\mathbf{I - Q = \Delta S},$$

where I = input, Q = output, ΔS = change in storage. Input refers to precipitation (both rain and snow), whereas output generally refers to runoff and evapotranspiration. The change in storage refers to gain or loss of water stores from vegetation, channels, lakes, wetlands, and soils. The loss of summer ground implies an increase in storage retention through delayed shallow-soil drainage or a concurrent increase in water table elevation and stream flow.

A series of activities and processes operating at increasingly larger scales influence hydrologic conditions within a forested stand (Figure 1). Climate has the most significant influence on the hydrologic cycle (Fu et al. 2004). Years with higher annual and/or summer precipitation levels yield wetter summer soil conditions compared to lower-precipitation years. Next in importance is the mountain pine beetle infestation, which can influence watershed- and stand-level water balance. In addition, the site-specific response is determined by upslope watershed characteristics such as geology, soil type, slope, and drainage density. Finally, on-site forest harvesting activities, including maintenance of natural flow patterns, use of different equipment, and soil disturbance, and understorey retention will also exert a local influence on hydrologic response at the site and watershed scales.

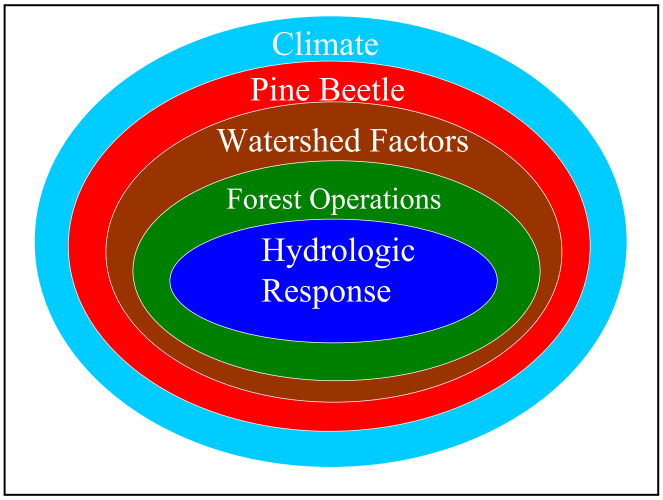


Figure 1. A conceptual model of process and watershed conditions that influence hydrologic response at the watershed and stand levels

1.1.1 Precipitation conditions in the Vanderhoof Forest District

Given climate's powerful effect on water balance, a climatological overview of the study area is provided as context to water-balance variability and the synergistic influence of MPB and climate. The following abridged analysis is an excerpt from a more detailed report by Ministry of Forests and Range research climatologist (Foord 2008)

Five Meteorological Services Canada (MSC) weather stations have been located in Vanderhoof area since 1916. This analysis focuses on data collected between 1980 and 2007, because the stations were most similar, being at the same elevation and only 2.2 km apart. Further, this recent period of data provides a relevant climatic context to concerns about the loss of summer ground. Annual and seasonal trend analysis for precipitation was assessed using a *t*-test of slope.

The climate data analysis identified the following important precipitation trends:

- Annual precipitation has increased over historical levels but not significantly (Table 1);
- Precipitation levels were higher from 1980 to 1996 than from 1997 to 2005;
- The ratio of summer to winter precipitation has increased significantly since 1997. Summer months between 1997 and 2007 received more precipitation than they did from 1980 to 1996;
- The summers of 2005 and 2007 were the wettest on record.

1.1.2 Precipitation trends between 1980 and 2007 at the Vanderhoof climate station.

Table 1. Precipitation trends between 1980 and 2007 at the Vanderhoof climate station.

Vanderhoof(3) 1980–2007	Trend	Change	T-test of slope, differs from 0, 90%
Annual total precipitation	Increasing	10.2%	Not significant
Winter precipitation	Decreasing	–45.1%	Significant
Spring precipitation	Increasing	26.1%	Not significant
Summer precipitation	Increasing	47.0%	Significant
Fall precipitation	Increasing	26.4%	Not significant
Annual rain-to-snow ratio	Increasing	67.0%	Significant
Annual rain	Increasing	33.8%	Significant
Summer rain	Increasing	47.3%	Significant
Fall rain	Increasing	43.9%	Significant

Between 2001 and 2003, summer precipitation totals (June to September) were within 4% of the 1971–2000 normal (Environment Canada 2008). Summer precipitation levels for 2004, 2005, and 2007 were considerably greater, ranging from 17% to 25% higher than the 30-year normal (Environment Canada 2008). The recent wetter summer seasons may affect heavy equipment use and harvesting activities in areas prone to poor drainage. Regardless of precipitation patterns, the reduced evapotranspiration in dead pine stands may raise groundwater levels.

1.1.3 Evapotranspiration processes

Dead and dying pine stands have lower transpiration and interception (evapotranspiration) rates than live trees (Bethalmy 1975; Putz et al. 2003; Tokuchi et al. 2004; Ladekarl et al. 2005). Interception levels vary between 15% and 35% among coniferous forest stands, depending upon precipitation amount and form, tree species, and stand characteristics (Dunne and Leopold 1978; Spittlehouse 2002; Banner et al. 2005). Similarly, transpiration varies depending upon geographic area, climate, tree species, and stand age. Knight et al (1985) determined that lodgepole pine stand transpiration levels accounted for 50% and 61% of total evapotranspiration in pine stands of southeastern Wyoming. Interception is still considered the important factor accounting for "watering-up"—a term used to refer to an increase in groundwater-table elevation following harvesting (Dubé et al. 1995). Harvesting trees allows for increased delivery of precipitation to the ground (i.e., net precipitation), because canopy cover is reduced. Similarly, as MPB-killed trees progress to grey attack, they drop needles, thereby decreasing interception of precipitation by up to 50% above pre-infestation levels (Boon 2007). This exceeds the reduction of evapotranspiration between 6% and 39% observed from sub-boreal watersheds subjected to harvesting alone (review by Plamondon 1993). Increased net precipitation is either stored or moved through the watershed. In those places where it is stored, water table elevation can increase, and soils may "water-up" (Dubé 1994). Alternatively, total annual water yield (i.e., river flow) may increase (Potts 1984; Sun et al. 2001).

In summary, changes in groundwater storage of VFD watersheds may be caused by changes in precipitation patterns or quantity, as well as changes to evapotranspiration processes. This project focused on the latter; specifically, determining what physical and biological characteristics predispose watersheds to the loss of summer ground as a consequence of the MPB infestation.

1.2 Forest harvesting and hydrologic effects

Although the focus of the project was to identify the influence of the MPB infestation on groundwater storage, salvage and previous harvesting may further influence the hydrologic regime of MPB-infested watersheds by leading to increased water table elevation (Dubé et al. 1995), as well as altering drainage patterns and increasing erosion rates (Jones et al. 2000). Altered drainage is a concern in areas with shallow groundwater tables where soils can be degraded by compaction and pooling during harvesting operations (Williamson and Neilsen 2000). If a stand's soil infiltration and water storage capacity are decreased due to the combined effects of soil disturbance and decrease in evapotranspiration of affected stands, it follows that surface soils will be wetter and surface-runoff duration and quantity will increase. Forest roads can intercept and redirect this increased runoff, altering natural drainage patterns and possibly increasing erosion rates (Bilby et al. 1989). Soil disturbance such as compaction can exacerbate water-logging (Aust et al. 1993; Groot 1998; Ballard 2000). Such possibilities are a significant resource management concern, due to the large spatial scale of the MPB epidemic and the understanding that the effect of excess soil saturation and compaction may persist for decades (Blake et al. 1976; Sharratt et al. 1997).

This project provides a watershed-level hydrologic risk assessment procedure to assess the relative risk of experiencing wet soils due to increased water table elevation and/or delayed surface drainage resulting from watershed characteristics and the MPB infestation. It uses a general model formula that requires commonly available information including forest cover, aerial photographs, soil data, and watershed assessment indicators. This general model approach was taken to facilitate its application by a variety of resource managers as a practical management tool. It provides information on the spatial scale of soil hydrology issues in the VFD, as well as provides a predictive operational tool for use in other districts dealing with the MPB and salvage harvesting activities. Our field investigation of the effect of the pine beetle outbreak on soil hydrology of British Columbia's central–interior watersheds allowed us to validate the procedure to predict the risk of operators encountering wet ground areas in those watersheds affected by severe MPB infestations.

2 Methods

To predict the risk of wet ground within selected VFD watersheds, the basic tenets of ecological risk assessment were followed. Each watershed was systematically evaluated using the same indicators to assess its likelihood of having wet ground relative to other watersheds. Given that there was limited field information to review, two approaches were used. The *a priori* approach (before-field assessment) predicted watershed risk based on indicators selected from the hydrologic literature and professional opinion. Following the collection of field data, the effectiveness of the *a priori* approach was determined, and field data were used to develop the *post-hoc* approach. The *post-hoc* approach consisted of an exploratory statistical review of field data to identify indicators that were most effective at explaining field-data variability. These indicators were then combined into a risk formula whose predictive efficacy was assessed, based on field observation.

2.1 The *a priori* approach

The ranking process provided here is the third iteration that was developed during the two-year study, based upon field observation and data analyses. It identifies two types of risk indicator groups: those identifying the potential for increased net precipitation (i.e., forest stand and mountain pine beetle infestation characteristics) and those identifying the potential for retention of increased net precipitation (i.e., physiographic characteristics of the watershed). Beetle infestation characteristics included measures of available rearing habitat (considered to be pine > age class 3), amount of grey-attack–stage pine trees, and the infestation-severity data from the 2004 aerial overview survey. Watershed characteristics include indicators of snowmelt and runoff conditions such as aspect (cooler aspects have slower snowmelt rates), drainage density (lower drainage density areas may have less ability to transport water to the channel), as well as a measure of existing soil sensitivity to high water tables, and soil moisture.

Indicators excluding forest cover were assigned a range of effect, from none (0) to large (1), as identified in Table 2. Scoring categories were selected to reflect the range of conditions identified for each indicator: low (0.3), medium (0.7), and high (1.0). Forest cover is a primary risk indicator, because the proportion of a watershed infested by MPB is limited by the amount of pine in that watershed. As a result, the pine content was given more weight than other indicators, as identified by the use of its percentage value; i.e., 0–100. The attribute and analysis processing techniques used for each indicator are provided in Appendix 1.

Table 2. Risk indicators for the a priori approach and their ranking values.

Risk indicator	Range of condition	Ranking
A. Potential for Increased Net Precipitation (MPB and Forested Stand Conditions)		
Forest cover	Pine-leading *percentage cover > age-class 3* Non-pine leading *Percentage pine > age-class 3*	 Percentage value Percentage value
Percent grey attack	Percentage of pine cover infected by beetle before 2002.	Percentage value
Mountain pine beetle severity (2004 overview flight)	*Severe* *Moderate* *Low* *None*	1.0 0.7 0.3 0.0
B. Potential for Increased Retention (Watershed Descriptors):		
Soil moisture	*Well Drained* Very xeric, xeric, submesic, mesic *Imperfectly drained* Subhygric *Poorly drained* Hygric, Subhydric, Hydric	0 0.5 1
Watershed % with sensitive Soils	0 0–10 10–20 20–30 >30	0 0.25 0.5 0.75 1.0
Watershed descriptors	Understorey score SBS dk SBSdw3 SBSdw2 SBSmc3 SBSmc2/ESSFmv1 Drainage density (km/km^2) 0–1 1–2 2–3 3–5	 1 0.75 0.5 0.25 0 1 0.75 0.5 0.25

2.1.1 Risk indicator rationale

2.1.1.1 Potential for increased net precipitation (MPB and forested stand conditions)

Forest cover: The higher the proportion of mature pine infected by MPB (assumed here to be > age-class 3), the less transpiration occurs at the watershed level.

Percent grey attack: As the affected tree progresses from red to grey attack, its interception role decreases as needles fall. Further, the older the age of attack, the longer the site has been exposed to the altered hydrologic regime. This indicates an increased likelihood of soil saturation for a standard climatic condition.

Mountain pine beetle severity (overview flight 2004): The overview flight data were collected in the fall of 2004 following standard techniques (BCMoF 2001a). Severity is nominally assessed as light (1%–10%), moderate (11%–29%), and severe (>30%).

2.1.1.2 Potential for increased retention (watershed descriptors)

Soil moisture: Soil moisture categories follow the accepted classes and characteristics adapted under the biogeoclimatic ecological classification (BEC) zones. These categories were subdivided into three general classes, including those that are well drained (very xeric–mesic), imperfectly drained (sub-hygric), and poorly drained (hygric–hydric).

Watershed percentage with sensitive soils: Soil and landform maps of the VFD (1:50,000) were colour-coded to identify fine soil types prone to shallow or perched water tables along with organic soils. These maps were digitized and projected within watershed boundaries to provide an estimate of watershed coverage with these soil types. Fine surface and organic soils will likely have higher ambient soil moisture conditions than coarser soil types; as net precipitation increases in MPB-affected areas, those sites with fine or organic soils will show greater soil-moisture response than coarser soil types.

Understorey score: Understorey can intercept throughfall from the overlying canopy. Schmid et al. (1991) concluded that multi-storied stands may not see increased net precipitation compared to pre-MPB attack. Scores are based on findings of Coates et al. (2006), who showed increased likelihood of meeting silviculturally acceptable stocking levels in the understorey (1000 stems/ha) in the following VFD BEC sequence: SBSdk; SBSdw3; SBSdw2; SBSmc3; SBSmc 2; and, ESSFmv1.

Drainage density: Is a measure of the amount of stream channel per unit area of a watershed, calculated as:

$$\mathbf{D = \Sigma L/A}$$

where D = drainage density, ΣL = sum of channel length in the watershed (km), and A = area of the watershed (km^2).

It provides an estimate of how efficiently water leaves an area during storms (Knighton 1998) by providing an index of relative distance between where rain falls and flowing channels (Hewlett 1982). For example, a watershed with a drainage density of 1 may have an average distance to water of 250 m, whereas a watershed with a density of 10 will have a distance of 25 m (Hewlett 1982). As drainage density increases, the likelihood of surface-drainage issues and/or water table level increase will decrease.

Forest stand and MPB characteristics influence the delivery of precipitation to the ground, while watershed characteristics influence runoff and retention processes. In our study, these two groups of characteristics were combined in the following risk formula to produce risk scores:

Risk Score =
[potential for increased net precipitation] *
[potential for retention of increased net precipitation]

Specifically:

Risk =
[(% watershed area of lodgepole pine > age-class 3 + % grey attack) * infestation severity] *
[(drainage density + soil moisture score + understorey score +area with sensitive soils)]

The above algorithm was applied, and the resulting scores were normalized to fit a scale of 100 for ease of presentation. (Contact the author to view the *a priori* hydrologic risk ranking.) Risk categories were assessed as low for the lower quartile (0–25), moderate for the second quartile (25–50), and high for the third and fourth quartiles (50–100).

For illustrative purposes, the following examples are provided:

Case 1: Pine-leading (60% cover), low MPB severity, SBSmc2, 5% sensitive soils, drainage density of 4.5 km/km^2, sub-mesic soils ***– Low Risk***

Case 2: Pine-leading (60% cover), moderate MPB infestation, SBSdw3, 5% sensitive soils, drainage density of 1.2 km/km^2, level slope, mesic soils ***– Moderate Risk***

Case 3: Pine-leading (60% cover), severe MPB infestation, SBSdw3, 25% sensitive soils, drainage density of 0.8 km/km^2, level slope, sub-mesic soils ***– High Risk***

2.1.2 Indicators removed from the analysis during earlier iterations

Aspect: Although it is an important hydrologic indicator, aspect was removed from our analyses, because, in the predictive ecosystem model (PEM2) dataset used for this exercise, aspect is linked to slope, and many watersheds had low slope or were level and were not given an aspect value. In other districts, aspect should be reconsidered, because it affects snowmelt processes and summer exposure. For example, many northern-aspect watersheds (including NE and NW) will see a delayed spring runoff and contribute more snowmelt to ground than will watersheds of other aspects (Dingman 2002).

Average Slope: Average slope values provided by the PEM2 were removed, because most watersheds in the VFD had an average gradient of less than 10%. Other district-based versions of this process should consider average slope: as it increases the potential for soil retention decreases, because surface-water delivery to the channel is more effective (Dingman 2002).

Percentage of Steep Areas: This indicator was removed and replaced with the drainage-density measurement, which also incorporates topographic influences (Knighton 1998) and provides more detailed site information than average slope values.

2.2 Site classification and study design

Sites were located in several BEC zones, but were typically in the predominant zones of the Vanderhoof Forest District, namely the SBSmc2/3 and SBSdw2/3 BEC zones (Table 3). Watersheds were pine dominant, with forest-stand coverage ranging between 41% and 97%. Sites were generally classified further as having dry or average soil moisture levels

Study sites were located in the lower reaches of selected watersheds to ensure similar sampling environments between watersheds. To verify the level of predicted risk, two assessment approaches were used in this investigation: qualitative assessment and detailed assessment. The detailed assessment provides more specific and continuous information at seven sites, whereas the qualitative assessment provides less detail at 10 sites. Used in combination, they provide a sample size of about 10% of all third- and fourth-order watersheds in the VFD.

2.2.1 Qualitative assessment approach

Volumetric soil moisture content (θ) was measured at the toe, mid-slope, and summit positions, at 10 cm, 20 cm, 40 cm, and 60 cm depth. It was measured in late-summer and fall, when summer ground issues should be observed, using a modified impedance probe developed by Tsegaye et al. (2004) connected to a hand-held reader (Delta-T Devices Ltd., Cambridge, England). Volumetric soil moisture content above 30% was considered to be at levels where harvesting equipment may cause soil disturbance and experience operational difficulties (McNabb et al. 2001).

Table 3. Study watershed characteristics and assessment approach for sites established in 2005–2006

Watershed	Assessment approach	BEC zone	Area (ha)	% Pine over age class 3	MPB severity	Average slope & aspect [1]	Soil moisture
Peta Creek	Detailed	SBS mc2	1747.5	77.8	Low	<10%, none	Sub-mesic
Angly Lake	Detailed	ESSF mv1	609.9	73.5	Low	10.1-25%, cool	Mesic
Chowsunkut Lake	Qualitative	SBS dw3	3605.6	57.4	Severe	< 10%, none	Mesic
Belisle Creek	Detailed	SBS dw3	3764.1	97.9	Severe	< 10%, none	Sub-mesic
Cobb Lake	Detailed	SBS dw3	1078.1	75.9	Low	< 10%, none	Sub-mesic
Crystal Lake	Detailed	SBS mc3	4157.0	76.2	Moderate	10.1-25%, cool	Sub-mesic
Pitka Creek	Detailed	SBS dw3	489.8	41	Low	< 10%, none	Very xeric
Targe Creek	Detailed	SBS dk	18996.2	61.4	Severe	< 10%, none	Sub-mesic
Targe Creek-46km	Qualitative	SBS dk	18896.2	61.4	Severe	< 10%, none	Sub-mesic
Shaydee	Qualitative	SBS dk	5851.7	47.3	Low	< 10%, none	Mesic
10557	Qualitative	ESSFmv1	15069.2	64	Low	< 10%, none	Sub-hydric
10330	Qualitative	SBS mc3	1260.9	69.6	Low	< 10%, none	Sub-mesic
10426	Qualitative	SBS mc3	1962.7	72.9	Moderate	< 10%, none	Sub-hydric
10610	Qualitative	ESSFmv1	3354.3	70.2	Low	< 10%, none	Sub-hydric
10411	Qualitative	SBS dk	6108.7	66.5	Moderate	< 10%, none	Very Xeric
10573	Qualitative	SBSmc2	775.3	59.1	Moderate	< 10%, none	Mesic
10485	Qualitative	SBSmc2	1320.3	81.9	Moderate	< 10%, none	Sub-hydric

[1]Based on PEM data if the watershed is level (i.e., has no aspect).

2.2.2 Detailed assessment approach

Detailed assessment sites had nine wells located along forested and harvested slopes. Specifically, three wells were installed along a transect at the level summit, middle slope and toe slope of the harvested and forested sites to study the range of variability in soil hydrologic properties (Banner et al. 1993; Pennock et al. 1994). Soil structure–texture conditions were confirmed in proximal pedons to ensure within-site characteristics are as uniform as possible.

Field measurements were gathered at 2- to 3-week intervals in spring, summer, and early fall, when water table elevations were expected to decrease between the spring runoff and the summer months, with some recharge during early fall storms. This sampling frequency also allowed for observation of any surface ponding, soil saturation, and surface flow due to recent precipitation events (as measured by a proximal rain gauge).

2.2.2.1 Water table depth

Shallow wells (<1 m) were excavated by auger and lined with a PVC pipe having a 4-cm interior diameter to stabilize the well walls and provide a standard reference point from which to measure water table depth (Weight and Sonderegger 2001). Water table depths were measured seasonally at each site using a dipper or electrical buzzer probe (Dubé et al. 1995; Weight and Sonderegger 2001). Water table depths less than 60 cm below surface were considered “shallow” and to be an operational concern, because the capillary fringe may be as high as 30 cm above the water table (unpublished data), indicating a reduced amount of soil available for storage during rainfall events

2.2.2.2 Soil water storage capacity

Nachabe et al. (2004) defines soil water storage capacity (SWSC) as the depth (volume per unit area or height of water) of water needed to raise a shallow water table to land surface. Maximum SWSC is reached once all available pore space is filled with water between 0 cm and 60 cm depth. Then, the shallow water table rises to land surface, initiating ponding or saturation-overland flow. A decrease in a soil’s SWSC could result in more rapid rise of water table and extended near-saturated conditions, which may become an important factor in both seedling establishment and runoff generation.

In this study, field estimation of SWSC was carried out by determination of repeated volumetric soil water content (θ) measured by capacitance techniques to 60 cm depth (ECH$_2$O-20 and ECH$_2$O-5 soil moisture probes by Decagon Devices Inc., Pullman, WA). ECH$_2$O-20 soil moisture sensors were installed horizontally at 10 cm, 20 cm, 40 cm, and 60 cm depths at each monitoring location. Capacitance probes were calibrated to each site's depth to ensure accurate and reliable surface volumetric soil moisture results (Czarnomski et al. 2005). Soil-specific calibration for ECH_2O-20 and ECH_2O-5 probes was conducted to increase soil water content measurement accuracy at each site. In the early stages of the project, large sources of variation between capacitance-measured water contents and gravimetrically determined water contents (error of ≤ 80%) demonstrated that although time-consuming, sensor calibration was necessary to provide accurate and reliable measurements of SWSC. The soil water storage capacity was calculated by interpolating between measured depths. Continuous monitoring of soil moisture was made possible by connecting the sensors to Em50 dataloggers (Decagon Devices Inc.). Based on hand test procedure for soil plasticity in the field and soil moisture content records from this study, a SWSC that drops below 5 cm of water indicated soil being at field capacity, herein defined as the amount of water remaining after gravitational drainage becomes negligible from a previously saturated soil.

2.2.2.3 Hydraulic conductivity

The saturated hydraulic conductivity (Ksat) is critical for quantifying changes in soil physical hydrological characteristics, as it provides an indication of how easily soil transmits water under saturated conditions. However, due to the presence of air, field measurements of saturated hydraulic conductivity rarely occur under completely saturated conditions; consequently, Ksat is referred to as field-saturated hydraulic conductivity (Kfs) when measured above the water table in the field (Reynolds et al. 1983). Kfs represents the maximum permeability of a soil to water under field conditions in the unsaturated zone, thereby accounting for air-bubble entrapment (Reynolds 1993). Field-saturated hydraulic conductivity was measured because it is particularly sensitive to soil disturbance (D. Reynolds, Agriculture Canada, pers. comm.) and, therefore, potentially an indicator of poorly drained soils. An increase in saturated areas may be identified by a decrease in Ksat capacity or excess delivery of runoff from upslope locations. However, runoff from upslope locations is not considered a significant source here because of the gentle slopes of the study sites. Instead, Ksat is emphasized, as it is largely controlled by the ability of saturated soils to accept more water during extended rainfall. Field-saturated hydraulic conductivity or ponded flow (Kfs) is determined by a simplified falling-head technique (SFH) developed by Bagarello et al. (2004).

Kfs was measured in three watersheds, consisting of one low-risk, one moderate-risk, and one high-risk site as determined by the *a priori* approach. Kfs data was measured in both forested areas and harvested areas at the summit positions to assess harvesting effect on soil drainage. Six randomly chosen $24m^2$-grid sampling areas were located within each of the forested and harvested areas. Within each grid, samples were drawn from 12 points.

Particle size was measured at five field sites chosen to cover the range of the hydrological risk gradient from the *post-hoc* risk approach; i.e., high risk (Cobb Lake, Targe Creek), moderate risk (Belisle Creek, 53 Km Road), and low risk (Pitka Creek) of decreased water table depth (Table 4).

Table 4. Particle-size distribution in top 10 cm soil in the beetle-infested and clearcut for the five selected sites.

	Condition	Texture Class	Clay (%) (<2 μm)	Silt (%) (2-50 μm)	Sand (%) (>50 μm)
Belisle Creek	MPB	Silty clay loam	33	58	9
	Clearcut	Silty clay loam	30	60	10
Targe Creek	MPB	Sandy loam	10	34	56
	Clearcut	Sandy loam	9	40	51
53km Road	MPB	Sandy loam	8	37	55
	Clearcut	Sandy loam	8	28	64
Cobb Lake	MPB	Sandy loam	7	25	68
	Clearcut	Sandy loam	6	28	66
Pitka Creek	MPB	Sandy loam	7	36	57
	Clearcut	Sandy loam	6	34	60

Soils were predominantly coarse and relatively uniform in texture within the top layer (0 cm to 10 cm depth) across the sites, except at Belisle Creek, which had a high clay content (Table 4). Within the sites, MPB and clearcut areas have similar particle-size distribution. To assess whether the conversion of summer to winter ground was influenced by harvesting activities, soil disturbance was assessed using the British Columbia Ministry of Forests procedures (BCMoF 2001b) on each sampling grid. The amount of disturbance was found to be negligible over all the experimental sites (i.e., sampling grids), except at Targe Creek, where ground surface was compacted and some scalping could be seen at each sampling point.

2.2.2.4 Other soil properties related to soil-structure characteristics

Field investigation of SWSC and hydraulic conductivity (HC) also requires complementary information about other soil properties, including particle size, organic carbon content, and bulk density. Particle-size distribution was determined from the fine-soil fraction having a <2-mm diametre by the hydrometer method (Gee and Bauder 1986) at each sampling point for measuring Kfs. Particle-size characteristics can explain differences in hydraulic conductivities between soils and depths (e.g. Bosch and West 1998). As well, at lower water content, HC variability is associated with variability of soil texture. At each of the watersheds studied, a soil description was completed according to the methods outlined in the *Field Manual for Describing Terrestrial Ecosystems* (BCMoF and BCMoE 1998). Soil orders associated with this study were classified in accordance to the Canadian System of Soil Classification (Soil Classification Working Group 1998) and are as follows: Orthic Dystric Brunisol (4), Orthic Humo-Ferric Podzol (3), Eluviated Dystric Brunisol (1), Orthic Gray Luvisol (1), Orthic Gleysol (1; see Appendix 2). Soil pH in 0.01 M $CaCl_2$ (Kalra and Maynard 1991) and organic carbon content (loss on ignition method; Tiessen and Moir 1993) were determined in order to confirm and supplement field identification and classification. Soil structure–texture conditions are paramount to the hydraulic properties of soils; however, forest soils are known to be very heterogeneous. Therefore, information on soil layering is essential in explaining variability in Ksat rates.

Although soil strength has emerged as an indicator for monitoring changes in soil physical conditions (Powers 2002), it is still being tested on forest soils in B.C. (Bulmer and Krzic 2003). Stony soils and rapid changes in soil moisture conditions near the surface in shallow-water-table environments make the use and interpretation of soil-strength measurements difficult in our study area. Therefore, in addition to a qualitative assessment (BCMoF 2001b), bulk density (Db) was also used to provide an index of soil compaction (or harvesting effect; Block et al. 2002). Bulk density was calculated on a wet-volume basis and determined by the core technique (Culley 1993), with two cores (4 cm long x 5 cm diameter) collected at the mid-point of the 10 cm and 20 cm depths at each HC sampling point.

2.3 The *post-hoc* assessment

To balance the *a priori* approach, whereby sites were selected ahead of field sampling based upon their risk of wet areas, a *post-hoc* assessment approach was taken at the end of the study to determine effective risk indicators based on field data. Specifically, effective risk predictors were determined using coarse- and fine-filtering approaches similar to those described by Berger and Entekhabi (2001). The coarse-filtering approach consisted of a principle components analysis (PCA) of field data to identify groups of correlated indicators that explained a high proportion of data variability (Manly 1994). Risk indicators include those identified for the *a priori* approach, as well as the topographic index and the relief ratio (both described below). Once groups of indicators were identified, they were fine filtered using a stepwise general linear model (GLM; Sokal and Rohlf 1995), which identified those indicators within the larger groups that had the highest predictive power for identifying field-verified “wet sites”.

The indicators added to the *post-hoc* assessment review include:

Topographic index: The topographic index quantifies the opposing tendencies of an area to collect subsurface flow from upslope areas and to transmit it downslope (Dingman 2002; Hjerdt et al. 2004). Typically, this metric would be applied on a smaller scale using digital elevation model information, but it is applied here to obtain a relative measure of the likelihood of runoff throughout the watershed.

It is calculated as follows:

$$TI = \ln(\text{watershed area}/\tan(\text{watershed slope}))$$

Relief Ratio: The relief ratio is a measure of basin-wide average slope, calculated as the elevation difference between the highest and lowest points in a watershed divided by the distance from the watershed outlet to the farthest point away. It provides a measure of topographic influence on lateral water movement: as the relief ratio increases, so should the lateral movement of water (Berger and Entekhabi 2001).

Relief ratio scores ranged from 0.01 to 0.20.

2.4 Study sites and the assessment approach

A total of 17 watersheds were chosen for study in 2005 to 2007 using the first risk assessment results. These include six low-risk, four moderate-risk, and seven high-risk watersheds, as identified by the *a priori* method (Table 5). The prominence of high- and low-risk watersheds was intentional to ensure suitable data quantity in order to show a substantial difference between these classifications. Within the 17 watersheds, seven detailed assessment study areas were established in 2005; the remaining 10 qualitative assessment areas were chosen in 2005 and 2006 (Table 5). Interviews with local stakeholders yielded another four candidate areas, but these were excluded after initial visits as required travel time was high and would prevent completion of monitoring at the established stations; further, each of these suggested areas consisted of complex and broken terrain areas with many collecting zones that would preferentially accrue water and bias results when compared to the gentle slopes used at the other 17 study sites.

Field information from 2006 and 2007 were used for the *a priori* and *post-hoc* assessment approaches, because those sampling seasons provided the most consistent datasets across all of the detailed and qualitative assessment sites.

2.5 Statistical analyses of field data

Water table data collected from well sites were found to be lognormally distributed during their review with normal probability plots in SYSTAT 11® software (Systat 2004). Data were transformed (Manly 2000) accordingly prior to an analysis of variance (ANOVA) and used to identify differences in water table depth across slope location, risk class, treatment (forested and cutblock), season, and year. Similar analyses were completed for soil moisture measurements collected at the qualitative assessment sites, but these data were not transformed as they were normally distributed. ANOVA for soil moisture data was completed using average soil moisture collected from the 10 cm, 20 cm, 40 cm, and 60 cm depths. Significance for all tests was determined at a level of 0.05.

Table 5. Predicted hydrologic risk for studied watersheds, their harvest level and the assessment approach used in 2005 to 2006.

Watershed	UTM coordinates (Zone 10)	Assessment Approach	Harvest Level	Hydrologic Risk – 2006
Peta Creek	381891, 6007454	Detailed	No Harvest	Low
Angly Lake	393427, 6013426	Detailed	No Harvest	Low
Cobb Lake	470959, 5975113	Detailed	>30% Harvest	Low
Pitka Creek	405900, 6017328	Detailed	>30% Harvest	Low
Shaydee	389259, 5972572	Qualitative	>30% Harvest	Low
10330	405752, 5959769	Qualitative	<30% Harvest	Low
10411	368335, 5949015	Qualitative	<30% Harvest	Moderate
10610	407623, 5942794	Qualitative	<30% Harvest	Moderate
10573	457971, 5948118	Qualitative	>30% Harvest	Moderate
10557	419347, 5940173	Qualitative	<30% Harvest	High
Crystal Lake	398316, 5961371	Detailed	No Harvest	High
Chowsunkut Lake	388944, 5980837	Qualitative	>30% Harvest	High
Targe Creek	386134, 5960090	Detailed	>30% Harvest	Moderate
Belisle Creek	392956, 5983659	Detailed	>30% Harvest	High
Targe Creek-44	373624, 5956749	Qualitative	<30% Harvest	Moderate
10426	407248, 5948258	Qualitative	<30% Harvest	High
10485	453823, 5942580	Qualitative	>30% Harvest	High

The Kfs values were found to be lognormally distributed, which shows that water movement strongly depends on the relationship between soil texture, bulk density, soil water content, structure, and other properties. Consequently, statistical analyses were conducted on ln-transformation of Kfs values. The geometric mean, minimum and maximum of the ln-transformed Kfs data were calculated. Results are reported both in the transformed scale and back-transformed scale by taking the antilog in the original units.

A group-t test (PROC TTEST) with the Cochran and Cox (1950) statistic was used to compare measurements of ln-transformed Kfs and normally distributed soil bulk density (Db) data within sites (MPB vs. clearcut). Effects of ln-transformed Kfs on the risk of loss of summer ground were tested by ANOVA using the GLM procedure (SAS Institute Inc. 2003).

The data for weekly SWSC values were analyzed after applying a square root transformation, because, following an examination of the residuals, they were not normally distributed. A Box–Cox transformation to this variable within the SAS Transreg procedure determined a square root transformation was best. A GLM procedure was performed on the transformed variable to test the effects of watershed risk, site conditions, and seasons on the storage capacity of the soil profile. Comparisons of all the different combinations were made using the Tukey–Kramer method on least-square estimates of means. Significance was determined at a level of 0.05.

3 Results and discussion

To facilitate the review of field data and the risk assessment process, findings are presented in sequence of summer/winter precipitation conditions, field assessment observations, and then a review of the *a priori* and *post-hoc* assessment model's effectiveness.

3.1 2006–2007 summer precipitation

Summer precipitation data for 2006 were not available for the Vanderhoof station (638 m elevation); instead, data were used from Environment Canada's station at Fort St. James (686 m elevation), city 50 km north by northwest from Vanderhoof. Although located at slightly different elevations, both Vanderhoof station and Fort St. James station are in the same biogeoclimatic zone and had similar average summer precipitations between 1981-2008 (respectively, 156 mm and 149 mm).

The 2006 snow pack for the Nechako River Basin was approximately 80% of the 1971 to 2000 normal, whereas the 2007 snowpack was approximately 150% of the normal (Figure 2; BCMoE 2008). In addition to the drier winter, 2006 total summer precipitation was approximately 20% lower than the 30-year normal (Figure 3; Environment Canada 2008). In contrast, following the wet winter of 2007, the summer also had increased precipitation levels: summer 2007 precipitation was approximately 17% higher than the 30-year normal (Figure 4; Environment Canada 2008). As a result, soils were expected to be relatively wetter in 2007 than in 2006. The precipitation data recorded by rain gauges at the detailed assessment sites mirror the general trends observed at the Fort St. James climate station for 2006 and 2007 (Figure 5).

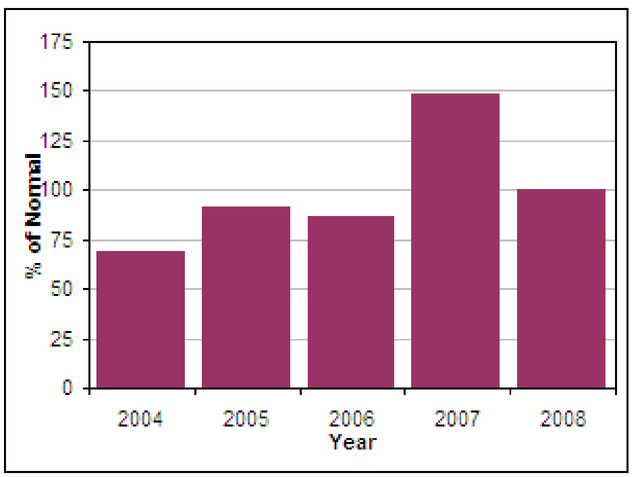


Figure 2. Annual snowpack level expressed as a percentage of the 30-year normal for the Nechako River Basin; i.e., 2004 was approximately 70% of the normal, whereas 2007 was close to the 30-year normal (100%). Data have been gathered from the provincial snow survey network and include observations from nine snow survey stations (BCMoE 2008).

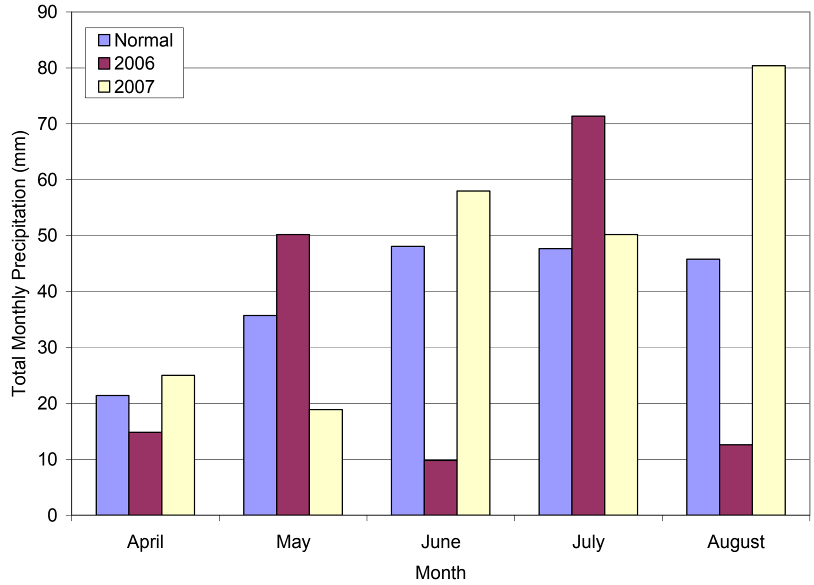


Figure 3. Fort St. James climate station (1092970) total monthly precipitation for the 30-year normal (1971 to 2000), as well as for 2006 and 2007.

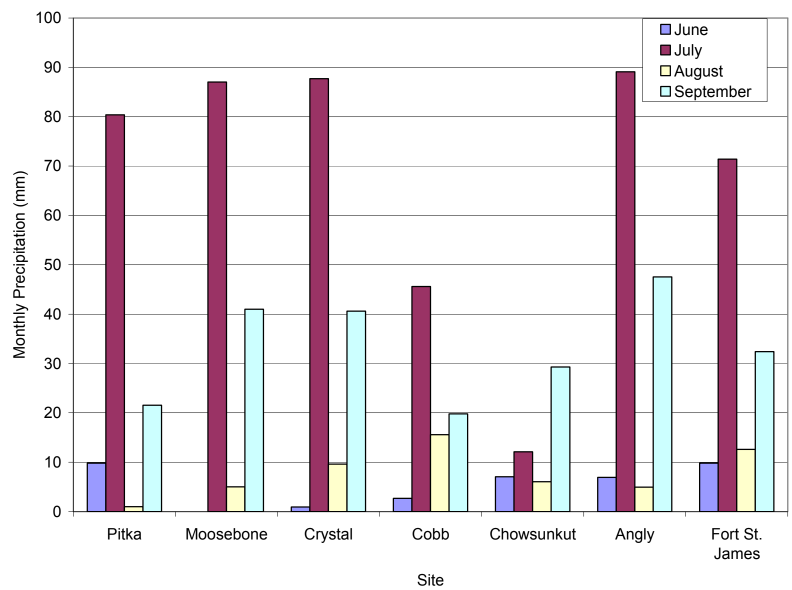


Figure 4. Rain gauge data for the detailed analysis sites and the Fort St. James Environment Canada station during the summer of 2006.

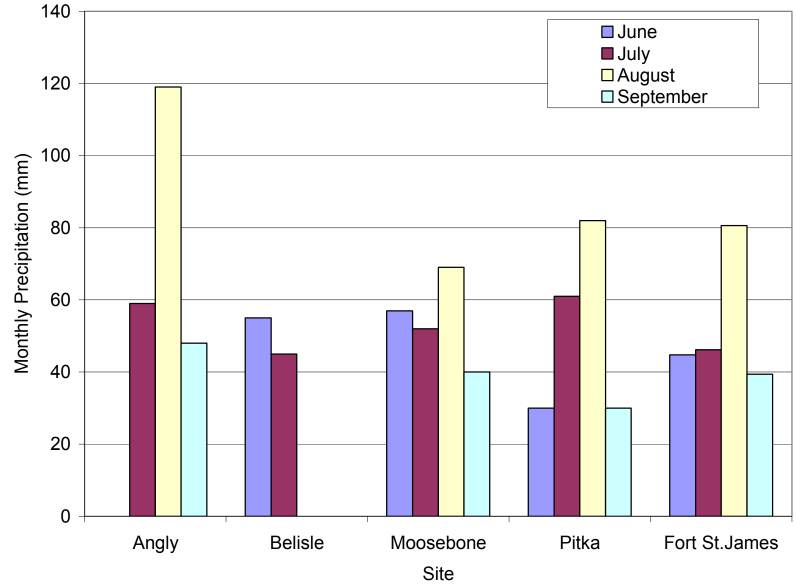


Figure 5. Rain gauge data for detailed assessment sites and the Fort St. James Environment Canada climate station (1092970). Angly site is missing June data; Belisle site is missing August and September data.

3.2 Field data assessment

3.2.1 Detailed assessment sites

3.2.1.1 Water table elevation

There was a significant slope location and seasonal effect (ANOVA, $p<0.05$) on depth to water table across all sites. Toe-slope locations had shallower water table levels than the other slope positions (Figure 6) and were most often above the 60-cm threshold used to identify wet locations in 2006 and 2007 combined. Summer rainfalls were higher in 2007 than in 2006; however, water table trends were similar between years. As expected, spring months had shallower (ANOVA, $p<0.05$) water table levels than the summer months (Figure 7).

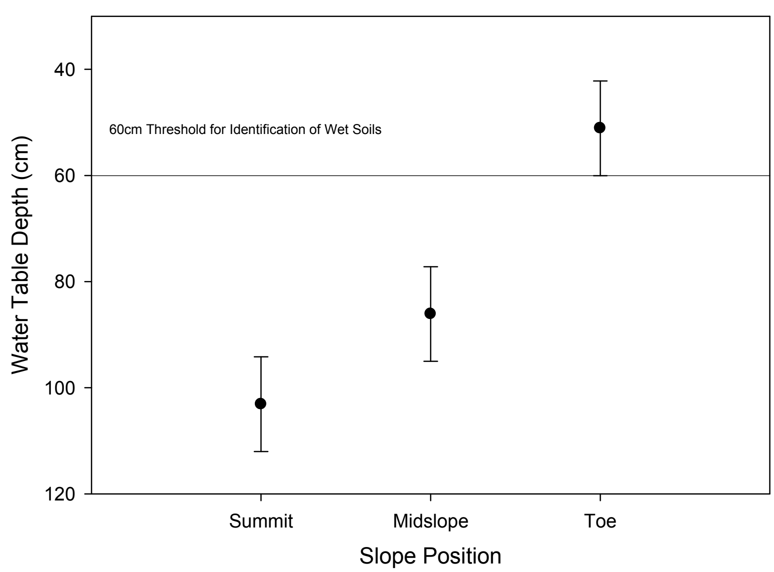


Figure 6. Average water table depth at each slope location during 2006 and 2007 (least squares mean and 95% CI, n=69).

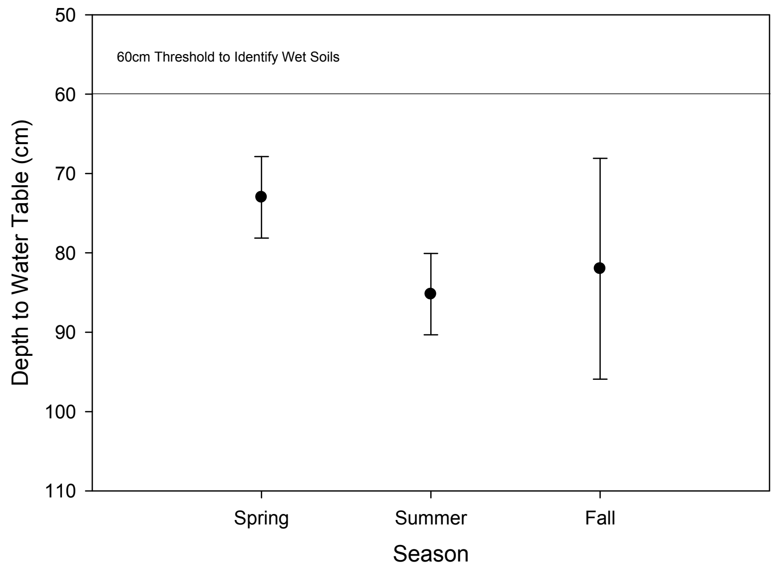


Figure 7. Average seasonal water table depths at all locations for 2006 and 2007 (least square means and 95% CI, spring and summer n=84, fall n=39).

3.2.1.2 Hydraulic conductivity

Measured values of lognormally distributed saturated hydraulic conductivities are shown in Table 6 for five sites distributed across the hydrological risk gradient. Not surprisingly, Kfs values vary greatly within and across the sites, with coefficients of variation (CVs) ranging between 62% and 161%. This variability is similar to what is reported from other field techniques for measuring Kfs. Kfs, like other soil hydraulic properties, typically exhibits large spatial variability primarily linked to texture (e.g., highest Kfs in Belisle Creek: silty clay loam; Table 4) and structure of soils (Hillel 1998; Kutilek 2004). Susceptibility to slaking that mainly occurs in surface layers (i.e., wetting effect on soil aggregate stability) and presence of binding agents such as organic matter (Tisdall and Oades 1982) are also likely to influence the soil hydraulic measurements. Kfs data were similar within site conditions (Table 6), but at the low end of saturated hydraulic range for coarse-textured soils (Hillel 1998). It may be that abundant presence of silt in the sand matrix (see Table 4) disperses and clogs up the conductive pores upon getting wet. Salvage-logging effect on drainage patterns was not clear, as saturated soil infiltration was not consistently lower in cutblock areas (Table 6). This may be due to the large sampling error or careful logging. However, compaction was evident at Targe Creek, as reflected by lower Kfs ($p<0.01$) and higher Db between 0 cm and 5 cm depth (Table 6) in clearcut, which showed that loss of summer ground can be attributed to poor drainage associated with soil disturbance. Despite the high clay content in the surface horizon of Belisle Creek soils, they had the highest Kfs rates due to soils crumb structure, which increased porosity (Table 6).. Another factor may have been the presence of water-stable aggregates that may result from sufficient organic matter combined with the non-swelling clay type present in the study area (Wuddivira and Camps-Roach 2007), but this was not quantified.

Table 6. Comparison of saturated hydraulic conductivity (Ksat) between the MPB and clearcut for the five selected sites. Kmean is geometric mean Kfs value, Kmax is maximum Kfs value, Kmin is minimum Kfs value, CV is coefficient of variation, and Db is soil bulk density.

Site	Condition	N†	Kmean	Kmin	Kmax	CV	Db (0cm–5cm)	Db (5-10cm)
			$x10^{-5}$ m s^{-1}			(%)	(Kg/m-3)	(Kg/m-3)
Belisle Creek	MPB	26	14.1a‡	3.7	74.6	73	933a§	1140a
	Clearcut	29	17.0a	3.0	51.1	79	972a	1070a
Targe Creek	MPB	28	8.1a	0.5	77.9	159	990a	1370a
	clearcut	33	3.2b	0.2	43.9	134	1150b	1380a
53km Road	MPB	10	4.4a	0.6	18.1	104	1084a	1311a
	clearcut	25	4.0a	0.1	22.4	161	1058a	1315a
Cobb Lake	MPB	25	8.3a	2.8	18.9	66	1071a	1275a
	clearcut	27	6.5a	2.3	31.9	75	1065a	1138a
Pitka Creek	MPB	30	4.0a	1.4	13.4	62	940a	945a
	Clearcut	27	8.5a	1.9	40.0	68	960a	980a

†Number of measurements

‡Different letters following geometric mean Kfs indicate significant differences between control and clearcut within the same site at $p<0.01$

§ Different letters following soil bulk density indicate significant differences between control and clearcut within the same site at $p<0.01$

3.2.1.3 Soil water storage capacity

Figures 8 and 9 display soil water storage capacity (SWSC) between 0 cm and 60 cm depth during a wet summer (2007) at two slope positions (toe and summit) for Pitka Creek and Targe Creek. The toe slopes had lower SWSC at both sites, regardless of site condition and season. Throughout the year, SWSC averaged 12% of the maximum SWSC and remained very close to or under the 5 cm threshold, indicating soil water storage conditions were near field capacity in toe-receiving areas (Figure 8). Summits were the best places to observe differences between sites. Targe Creek SWSC at the summit was higher than at the toe, but was still within the range of wet soil conditions—particularly so in the clearcut area (i.e., approx. 74% of water-filled pore space), whereas the Pitka Creek SWSC peaked at 62% (or 0.13 cm of water) and 74% (or 0.155 cm of water) of the maximum SWSC, respectively, in MPB and clearcut areas (Figure 9). Based on this high SWSC, the Pitka Creek summit position can be categorized as dry. A much larger amount of rainfall would be required to raise the water table to the land surface at Pitka Creek, lessening the risk that forest activities would be shut down at the site during rain events.

In the spring, SWSC was the lowest after snow melt had replenished the soil moisture. Soil pore space increased to reach its driest point in late summer. In the fall, the general trend was that soil moisture content slowly built up, possibly due to reduced evapotranspiration. However, the soil continued to drain in the absence of fall rain, as illustrated at Pitka Creek, which drained more efficiently than at Targe Creek (figures 8 and 9). Soil classification data identified that the high-risk Targe Creek had a shallow restricting layer between 40 cm and 60 cm depth (see Appendix 2) that impeded water movement: the soil was consistently wetter both at the toe slope and summit when compared to the low-risk Pitka Creek. Surprisingly, cutblock SWSC were not always lower than forested-area SWSC, despite lack of ground cover and understorey on the cutblock.

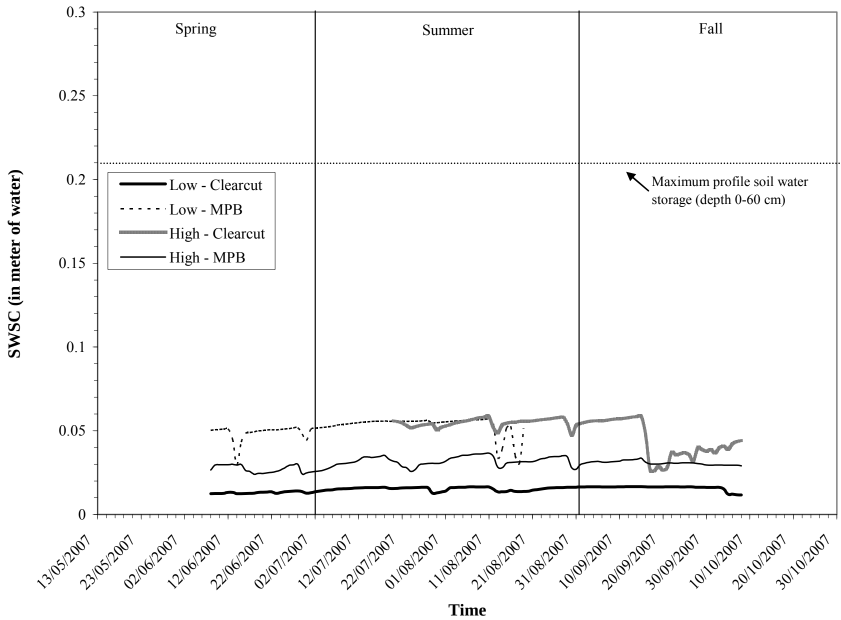


Figure 8. Toe-slope soil water storage capacity in 2007 (wet summer) within site conditions for Pitka Creek (Low) and Targe Creek (High) areas

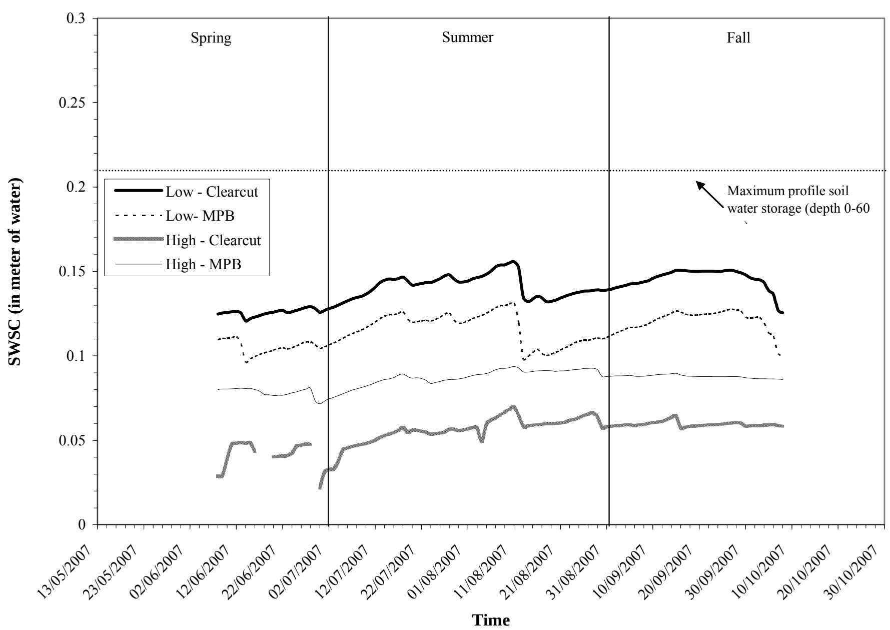


Figure 9. Summit soil water storage capacity in 2007 (wet summer) within site conditions for Pitka Creek (Low) and Targe Creek (High) sites.

3.2.2 Qualitative assessment sites

There were significant (ANOVA, $p<0.05$) year, seasonal, slope position, and treatment effects on volumetric soil moisture content at the qualitative assessment sites. The 2006 sampling season was drier than 2007 (Figure 10), as supported by the review of precipitation data. Not surprisingly then, more sites were identified as having wet soil conditions in 2007 than during the 2006 sampling period. Despite this annual difference, when these data were grouped, toe slope locations were found to be significantly (ANOVA, $p<0.05$) wetter than mid-slope and summit locations, the forest sites had lower average soil moisture levels than the cutblock sites had, and spring was the wettest season (figures 11, 12, and 13).

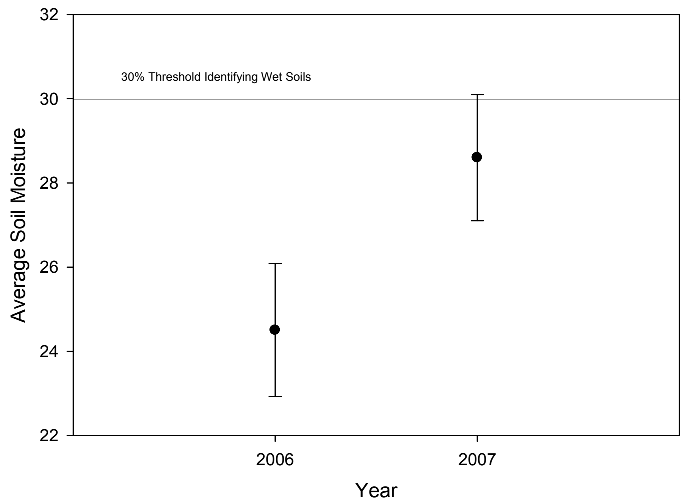


Figure 10. Average water table depths across sites and slope position, showing 2006 to be significantly drier than 2007 (least squares means and standard error n= 96).

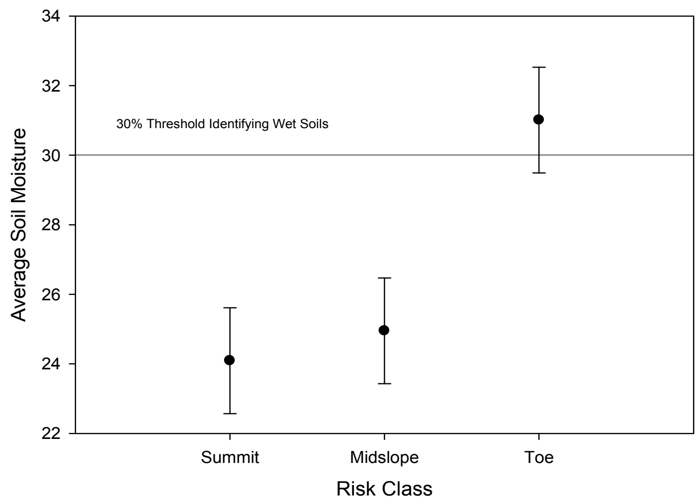


Figure 11. Average soil moisture conditions across risk class emphasizing significant difference between toe-slope and up-slope conditions (least square means and standard error presented n=64)

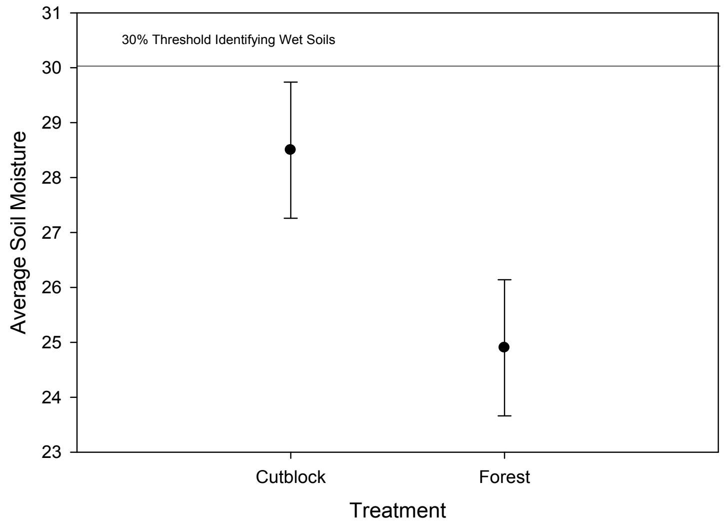


Figure 12. Average soil moisture conditions in 2006 and 2007, forested vs cutblock sites (least squares means and standard error n=96)

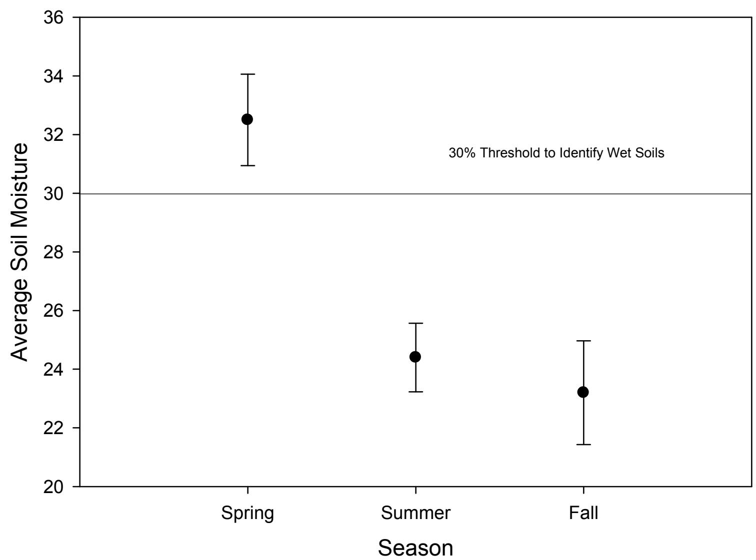


Figure 13. Average soil moisture conditions across seasons, identifying significantly wetter conditions during spring months (least squares means and standard error, fall n=42, spring n=54, summer n=96)

3.3 Field verification of the *a priori* risk assessment

The *a priori risk* assessment was not effective at distinguishing risk between sites based on measurements of water table depth at the detailed assessment sites (ANOVA, $p>0.05$) or measurements of soil moisture from the qualitative assessment sites (ANOVA, $p>0.05$). Comparing predicted risk class to field observations (Table 7), the *a priori* approach was correct only ~40% of the time. Risk rankings were considered correct when high-risk sites were wet in both the forest and cutblock locations, moderate sites were wet in the cutblock (due to the loss in transpiration), and low sites were dry in both locations.

3.4 The *post-hoc* assessment

The PCA of the water table and average volumetric soil moisture content identified two groups of indicators that explained 65% of field data variability (Table 8). The GLMs for water table and soil moisture data each refined this list of indicators and identified lodgepole pine content, understorey, drainage density, sensitive soils, and the topographic index as the most significant indicators in predicting water table height and soil moisture. Although each GLM analysis provided an equation to predict specific values for water table or soil moisture, these formulae are not presented here, because water table elevations and soil moisture cannot realistically be predicted at the watershed scale. Instead, these parameters were used to construct a new risk-prediction formula that is based upon the coefficient's scale and sign (i.e., positively or negatively correlated to depth to water table or soil moisture) for each indicator.

Table 7. Predicted risk and field verification data summary. Water table depth values identify whether the average condition was wet or dry during the summer months of 2007, the wettest summer during the sample period.

Watershed	Predicted Risk: 2007	Volumetric Soil Moisture Content ***Forest/Cutblock***	Water Table Depth ***Forest/Cutblock***	Soil Water Storage Capacity ***Forest/Cutblock***	Prediction Correct
Peta Creek	Low	N/A	Dry	Low/N/A	Correct
Angly Lake	Low	N/A	Dry	Low/N/A	Correct
Cobb Lake	Low	N/A	wet/wet	N/A	Underestimate
Pitka Creek	Low	N/A	dry/dry	Low/Low	Correct
Shaydee	Low	dry/dry	N/A	N/A	Correct
10330	Low	dry/dry	N/A	N/A	Correct
10411	Moderate	wet/wet	N/A	N/A	Underestimate
10610	Moderate	dry/dry	N/A	Low/Low	Correct
10573	Moderate	dry/dry	N/A	N/A	Correct
Targe Creek	Moderate	N/A	wet/wet	Low/Low	Underestimate
Targe Creek-44	Moderate	wet/wet	wet/wet	N/A	Underestimate
10557	High	dry/wet	N/A	N/A	Overestimate
Crystal Lake	High	N/A	Dry	N/A	Overestimate
Chowsunkut Lake	High	N/A	dry/dry	High/High	Overestimate
Belisle Creek	High	N/A	dry/dry	N/A	Overestimate
10426	High	dry/wet	N/A	N/A	Overestimate
10485	High	dry/dry	N/A	High/High	Overestimate

Table 8. Risk indicators that were most effective at explaining data variability, as identified by PCA. Note: the same indicators were identified for both measurements.

Measurement	Component	Indicator
Water Table Depth	1	Topographic Index
		Slope
		Understorey
	2	Relief Ratio
		Lodgepole Pine Content
		Sensitive Soils
		Drainage Density
Average Soil Moisture	1	Topographic Index
		Slope
		Sensitive Soils
		Relief Ratio
		Lodgepole Pine Content
		Understorey
	2	Drainage Density

In keeping with the *a priori* grouping of indicators, two groups were chosen for the *post-hoc* formula: the potential for increased delivery of precipitation to the forest soil, and the retention of precipitation reaching the soil surface. The *post-hoc* risk formula is:

Risk = (Lodgepole Pine Score / Understorey Score) * (Drainage Density Score / Sensitive Soils Score) * Topographic Index

Where:

Lodgepole Pine Score: < 30% cover (0.1); 30%–50% (0.3); 51%–70% (0.7); > 71% (1.0)

Understorey Score: SBS dk (0.10); SBSdw3 (0.25); SBSdw2 (0.5); SBSmc3 (0.75); SBSmc2/ESSFmv1 (1.0);

Drainage Density Score: <1 km/km^2 –(0.1); 1 km/km^2–2 km/km^2 (0.25); 2 km/km^2–3 km/km^2 (0.5); 3 km/km^2–4 km/km^2 (0.75); > 4 km/km^2 (1.0)

Sensitive Soils Score: 0% of watershed area (1.0); 0%–10% (0.75); 10%–20% (0.5); 20%–30% (0.75); >30% (0.1))

Topographic Index: dimensionless value; calculated range here is between 5 and 14, with increasing values representing a decrease in watershed slope for a given-size watershed.

This formula is more hydrologically relevant than that presented for the *a priori* approach: it gives weight to inherent buffers to the loss of summer ground, including understorey, soil type, and the relative slope of the watershed. For example, understorey can lower the increase in net precipitation (Schmid et al. 1991), areas with less sensitive soils may have better drainage than those with sensitive soils, and the area-based slope of the watershed provides insight as to the retention time of water on the soil surface (i.e., the lower the slope by area, the lower the runoff potential; Dingman 2002).

Scores generated by the *post-hoc* formula were ranked from 1 to 100, with ties receiving the same rank (i.e., 50, 51, 51, 52 were ranked 50, 51.5, 51.5, 53). High-risk sites were those with the upper 25 percentile of ranked scores (i.e., 1–25), moderate-risk sites were the middle 50 percentile of scores (26–74), and low-risk watersheds were the lower 25 percentile of scores (75–100).

Once ranks were determined, field data for water table depth and soil moisture were once again subjected to ANOVA, using the new risk classes as a main effect, with the analysis grouped by slope location (because all toes were wet). This analysis identified that the *post-hoc* risk assessment approach was a significant factor for predicting both water table and soil moisture ($p<0.05$). Comparing predicted risk class to field observations (Table 9), the *post-hoc* approach was accurate approximately 94% of the time. As during the *a priori* review, risk rankings were considered accurate when high-risk sites were wet in both the forest and cutblock locations, moderate-risk sites were wet in the cutblock, and low-risk sites were dry in both locations. A risk map of summer-ground loss was produced to assist forest planners in the VFD (see Appendix 3).

Table 9. Predicted risk and field verification data summary for the *post-hoc* assessment. Table values identify whether the average condition was wet or dry during the summer months of 2007, the wettest summer during the sample period.

Watershed	*Post-hoc* Predicted Risk: 2007	Volumetric Soil [1] Moisture Content *Forest/Cutblock*	Water Table Depth *Forest/Cutblock*	Soil Water Storage Capacity *Forest/Cutblock*	Prediction Correct
Peta Creek	Low	N/A	dry	Low/N/A	Correct
Angly Lake	Low	N/A	dry	Low/N/A	Correct
10573	Low	dry/dry	N/A	N/A	Correct
Pitka Creek	Low	N/A	dry/dry	Low/Low	Correct
Shaydee	Low	dry/dry	N/A	N/A	Correct
10330	Low	dry/dry	N/A	N/A	Correct
10557	Moderate	dry/wet	N/A	N/A	Correct
Crystal Lake	Moderate	N/A	dry	Low/Low	Correct
Chowsunkut Lake	Moderate	N/A	dry/dry	N/A	Correct
Belisle Creek	Moderate	N/A	dry/dry	Low/Low	Correct
10485	Moderate	dry/dry	N/A	N/A	Correct
10610	Moderate	dry/dry	N/A	N/A	Correct
10411	High	wet/wet	N/A	N/A	Correct
Targe Creek	High	N/A	wet/wet	High/High	Correct
Targe Creek-44	High	wet/wet	wet/wet	N/A	Correct
10426	High	dry/wet	N/A	N/A	Overestimate
Cobb Lake	High	N/A	wet/wet	High/High	Correct

3.4.1 Water table depth

High-risk watersheds had significantly shallower depth to water table at the summit across years (Figure 14; $p<0.05$). Harvesting effects on water table depth were not detectable, as dead and dying pine stands possibly had transpiration loss and increased water delivery to soil more comparable to cutblock areas than to non-infested stands at toe-slope and summit locations (figures 15 and 16). High-risk sites had the shallowest water tables—on average, at least 25 cm shallower than in moderate-risk and low-risk sites (Figure 14) and, as a result, risk of experiencing wet soils was greatest at these sites. However, the water table never rose above 60 cm at the summit during the year and is likely not an operational concern (Figure 17). Mid-slope water table was not affected by risk, season, or site condition, because mid-slope water is mostly controlled by gravitational drainage (Figure 18, $p<0.05$).

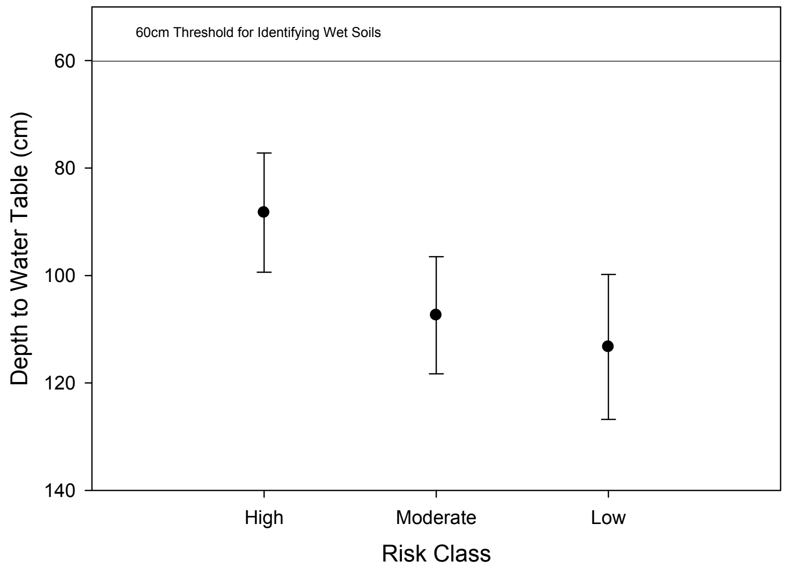


Figure 14. Average depth to water table at the summit location for each risk class (error bars represent 95% CI, n=24 high, 20 moderate, 25 Low)

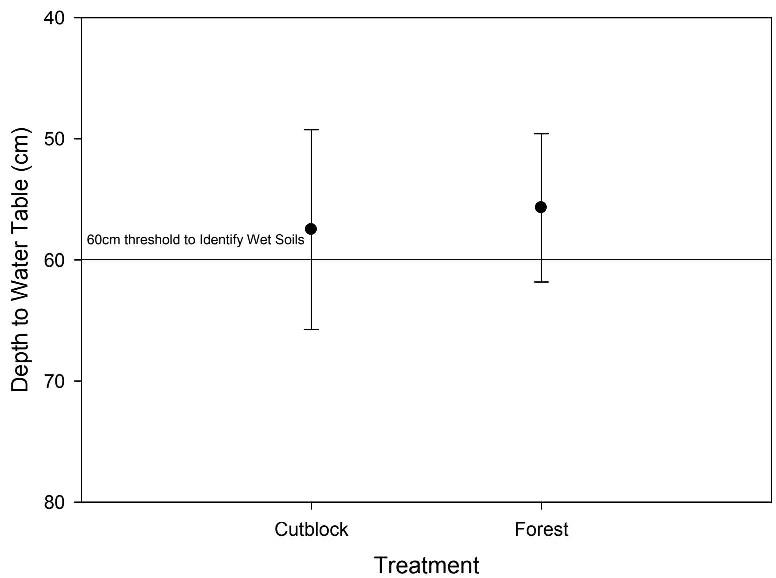


Figure 15. Average depth to water table at the toe-slope position (error bars represent 95%CI, n= 27 cutblock, 42 forested).

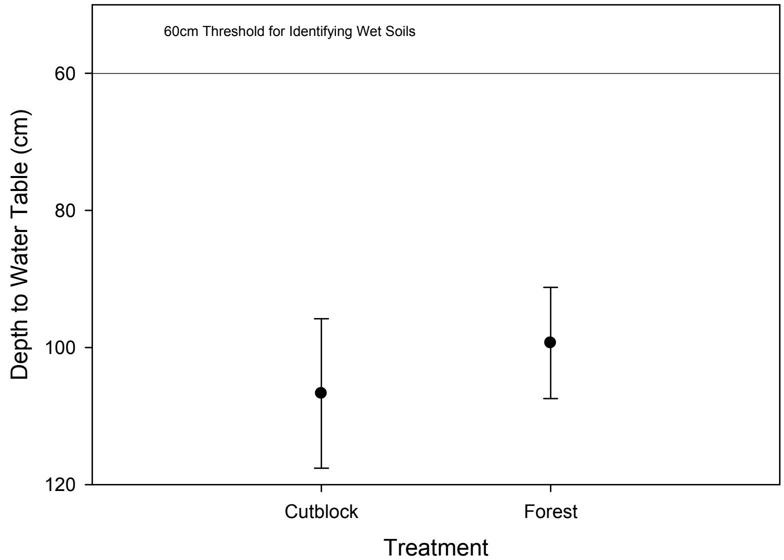


Figure 16. Average depth to water table at the summit position (error bars represent 95% CI, n= 27 cutblock, 42 forested)

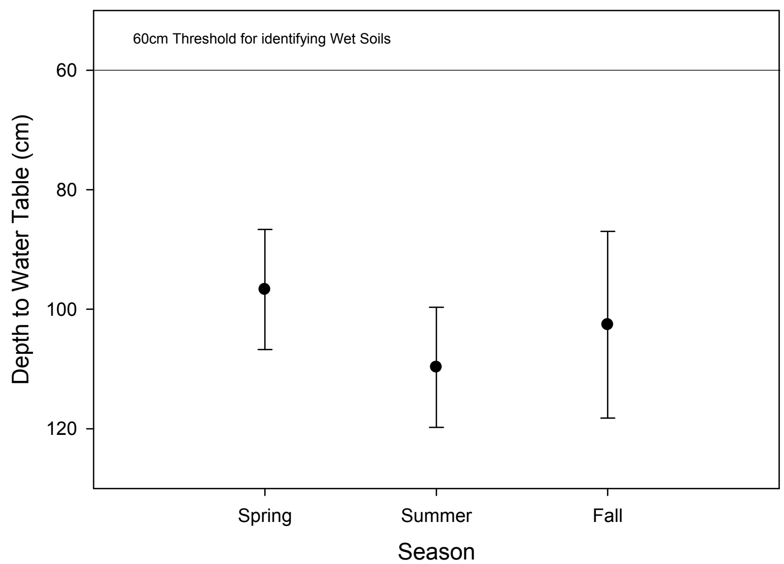


Figure 17. Average seasonal depth to water table at the summit position (error bars represent 95% CI, n=13 fall, 28 for spring and summer)

At the toe-slope locations, all sites were wet regardless of risk level and site condition (figures 19 and 15). Toe slopes showed higher water table levels in spring than in summer, whereas water table levels were the same across seasons for mid-slope and summit positions. Deepest water table levels were recorded in the fall, suggesting effects of spring runoff on toe-receiving areas diminishes over time until fall precipitation replenishes the soil moisture. This effect was strongest on low-risk sites (data not shown). However, water table levels remained within 60 cm of land surface throughout the year, so operation and movement of heavy equipment is not advisable at toe slopes, except for on low-risk sites in the fall (Figure 20). Separate water table analyses for 2006 (dry year) and 2007 (wet year) produced similar results, although wet-soil issues may be less common during a drier year (e.g., after a long dry spell in fall of 2006).

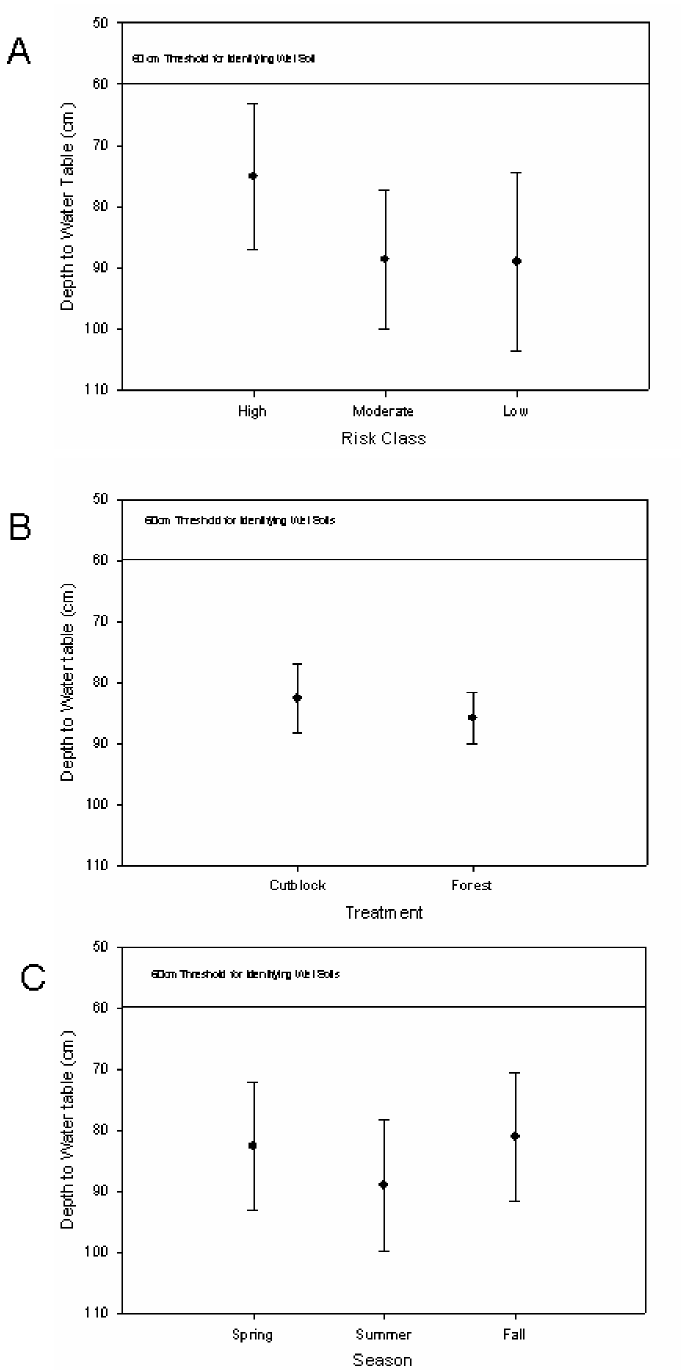


Figure 18. Mid-slope average depth to water table by risk, treatment, and season (error bars represent 95% CI, n=24 High, 25 moderate, 20 low, 27 cutblock, 42 forest, 28 spring, 28 summer, 13 fall).

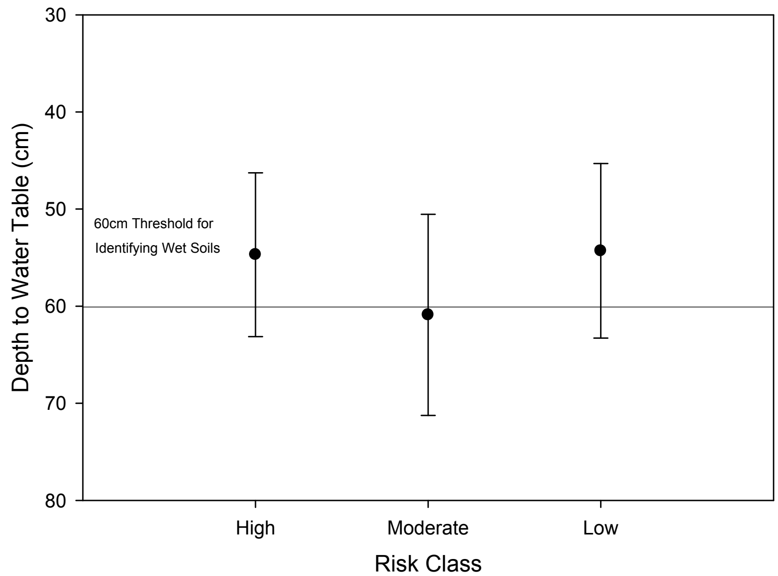


Figure 19. Average depth to water table at the toe slope for each risk class (error bars represent 95% CI, n = 24 high, 20 moderate, 25 low)

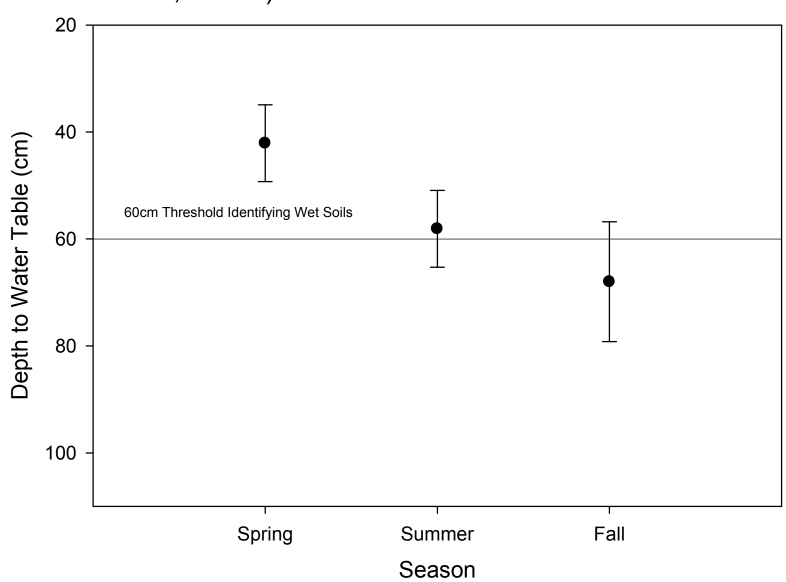


Figure 20. Seasonal average depth to water table at toe slope locations (error bars represent 95% CI, n=27 spring and summer n=13 for fall)

3.4.2 Field-saturated hydraulic conductivity

Analysis of ln-transformed Kfs from all sites indicated a statistically significant effect on watershed risk and site condition (Figure 21, $p<0.01$). The greatest measured hydraulic conductivities were found in the high-risk forested sites. In contrast, moderate-risk clearcut areas had the lowest Kfs, but soil disturbance was not observed during the soil disturbance surveys. Great variability in Kfs, in part due to very high spatial variability in soil properties, may explain this result.

Based on our sampling, harvesting did not lead to a significant reduction in Kfs across watershed risk, as is illustrated in Figure 21. There was faster surface drainage in the high-risk MPB areas than in the low-risk MPB areas. This indicates that differences in Kfs may not be explained by high water table levels, which are less likely to occur where surface drainage is fast. Hard, almost-cemented layers less than 60 cm deep that would impede drainage were observed at high- and moderate-risk sites and might be a controlling factor (e.g., Targe Creek, watersheds 10557 and 10426; Appendix 2). Although not impervious to water, the naturally compacted layers have a slower percolation rate that may be inadequate to drain large quantities of water reaching the soil in stands with a dead pine overstory or in large salvage-harvested areas. Under these conditions, soil saturation persists longer after spring runoff, and large summer storms can quickly fill the soil profile and raise the water table quickly, which may impede forest management activities.

The influence of pre-existing conditions in the soil profile such as the hard, almost-cemented layers can be exacerbated by compaction and may result in a higher risk for salvage-logged areas. For example, there was a statistically significant relationship between site condition and Kfs ($p<0.01$) at Targe Creek (Table 6). Compaction was evident in the clearcut sampling areas: bulk density increased significantly in the top 5 cm of soil following skidding (Table 6). These compacted areas were characterized by a platy structure and loss of original structure. The reduction in large spore space in the clearcut, which is responsible for most of the saturated flow, produced an average Kfs rate of 3.2×10^{-5} m s^{-1} (or 115 mm/h); this represented a reduction of 57% in Kfs from the MPB forest sites. However, the compacted soil surface would probably be able to move rainfall water during a typical heavy summer storm event (e.g., 10.8 mm/h on August 16, 2007). Startsev and McNabb (2000) also found harvesting effects on field-saturated hydraulic conductivity.

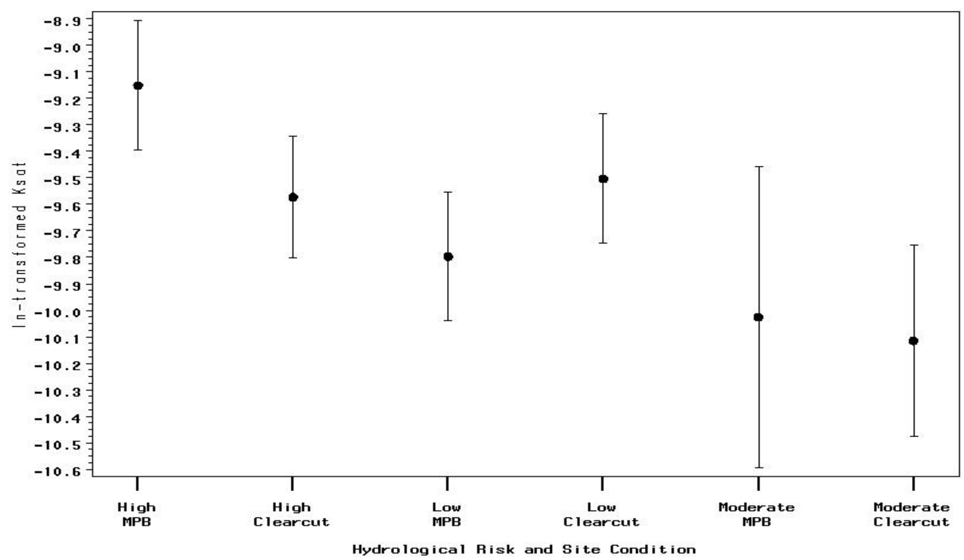


Figure 21. Least square mean estimates of ln-transformed Kfs (circles) by watershed risk class and site condition (error bars represent 95% CI, n=260).

3.4.3 Soil water storage capacity

Toe-slope locations were wet at all forested and harvested sites across all risk levels and seasons due to translocation of finer-textured material downslope and the locations' moisture-receiving position in the landscape (Figure 8). As expected, these results are consistent with the water table data analyses and concurrent SWSC response (i.e., low storage capacity leads to decreased water table). In comparison, risk effects on profile storage show more contrast at summit locations (Figure 9). Because of this, we excluded toe-slope locations (a confounding factor) and performed statistical analyses based only on summit position so that toe-slope data would not mask differences between risk, condition, season and SWSC. In 2006 (the drier year), the SWSC was lowest in the high-risk watershed (Figure 22; $p<0.05$). Moderate- and high-risk sites showed similar SWSC. During the wetter summer (2007; Figure 23), the association between watershed risk and SWSC was more evident ($p<0.05$). The high-risk watershed had the most reduced SWSC, followed by moderate-risk and then low-risk watersheds, which had the most pore space to store water. When the water table was the closest to ground surface during 2007, the low-risk site (Pitka Creek) had more than twice the SWSC compared to the high-risk site (Targe Creek; Figure 9). Because of the high soil water content, the water table here responds quickly to summer rainfall and leads to poor bearing capacity of the ground during logging. The lower the soil profile storage capacity is, the greater the risk of losing summer ground; this can be predicted from our *post-hoc* assessment approach.

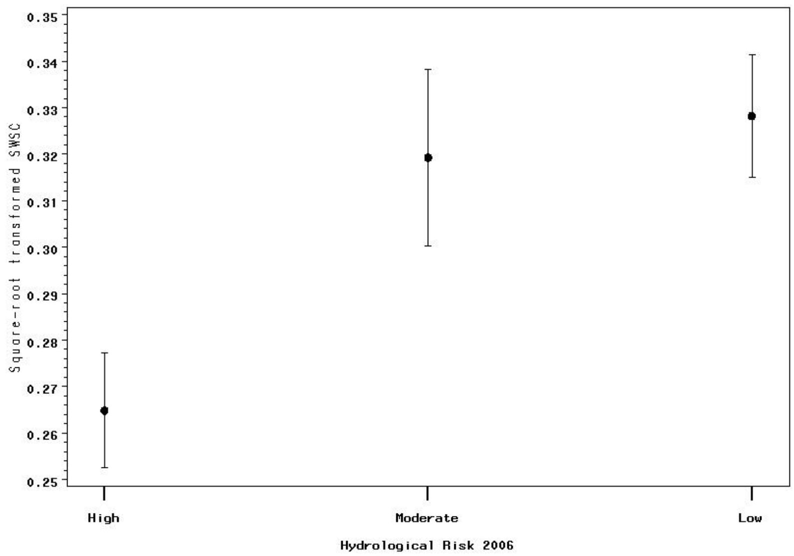


Figure 22. Least square mean estimates of square root transformed SWSC (circles) by watershed risk class in 2006 (error bars represent 95% CI, n = 588).

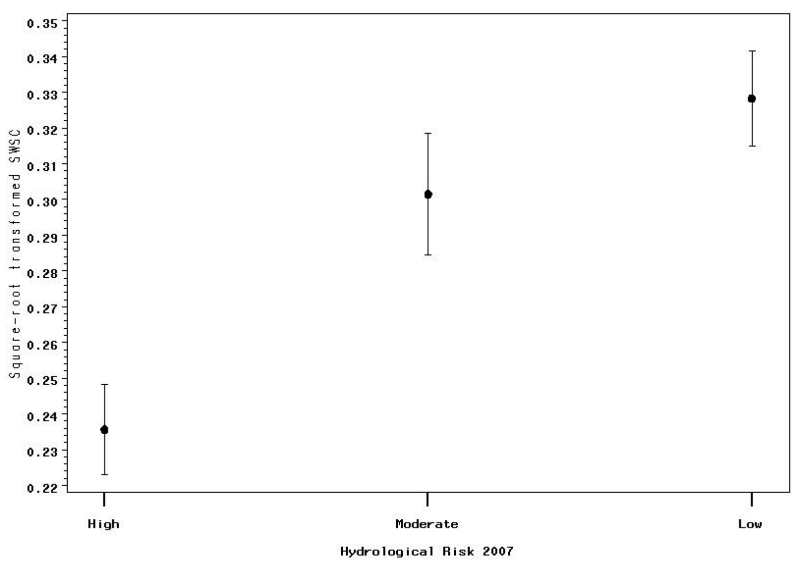


Figure 23. Least square mean estimates of square root transformed SWSC (circles) by watershed risk class in 2007 (error bars represent 95% CI, n = 295).

The site condition most susceptible to waterlogging was the clearcut treatment type during the wet summer of 2007. Reduced SWSC in clearcut areas compared to MPB stands was more pronounced in high and moderate watershed risk levels (Figure 24). Average SWSC data in the clearcut summit (from back-transformed scale) were 4.7 cm of water in high-risk levels and 8.8 cm of water in moderate-risk levels, compared to 6.8 cm and 12 cm, respectively, in the MPB stands. Therefore, it would have taken between 36% and 42% less water from rainfall to fill up the voids in the soil and raise the water table to the land surface in the clearcut than in the MPB. A typical 24-hour summer storm event (e.g. 35 mm on August 12, 2007) would be sufficient for water to pond in clearcut areas and to convert a soil from dry to wet in an MPB-affected stand within high-risk areas (figures 1 and 2). SWSC data were not corrected for encapsulated air,[1] which can substantially reduce available soil water storage, so SWSC may actually be lower than presented here (Constantz et al. 1988; Nachabe et al. 2004).

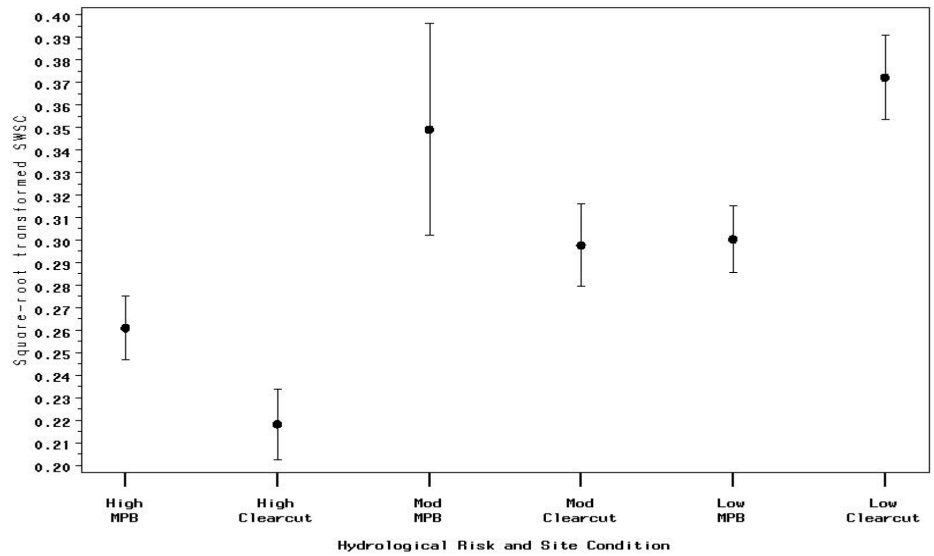


Figure 24. Least square mean estimates of square root transformed SWSC (circles) within watershed risk class and site condition (error bars represent 95% CI, n = 295).

Unexpectedly, as Figure 24 shows, low-risk SWSC data were lower in the MPB stand. This is likely due to inadequate sampling (one clearcut area). Winter ground was commonly observed at the toe slope regardless of risk and site conditions (except at Belisle Creek – MPB site; Figure 8), and persisted throughout the year because of a high water table (figures 19 and 20) and low SWSC.

There were seasonal and risk interactions on the transformed SWSC data ($p<0.05$; Figure 25) in 2007. SWSC in the high-risk sites was lower in spring than in summer and fall, although the water tables were the same across seasons (Figure 17). This indicates that the high water retention of some soils can significantly influence soil water content whether water table depth fluctuates or not and, therefore, contributes to a rapid rise in water table following a storm event. Within high-risk sites, barring major storm events, SWSC increased throughout the growing season as water slowly drained out of the soil following spring recharge (figures 8, 9, and 25). However, moderate-risk sites and low-risk sites had similar average SWSC across seasons (Figure 25). This indicates that the low-risk and moderate-risk sites are more capable of moving excess water compared to high-risk sites. Correspondingly, the low-risk and moderate-risk sites may have lower soil moisture and water table depth following storm events.

[1] Herein defined as the volume of air trapped in the soil below the water table as it rises

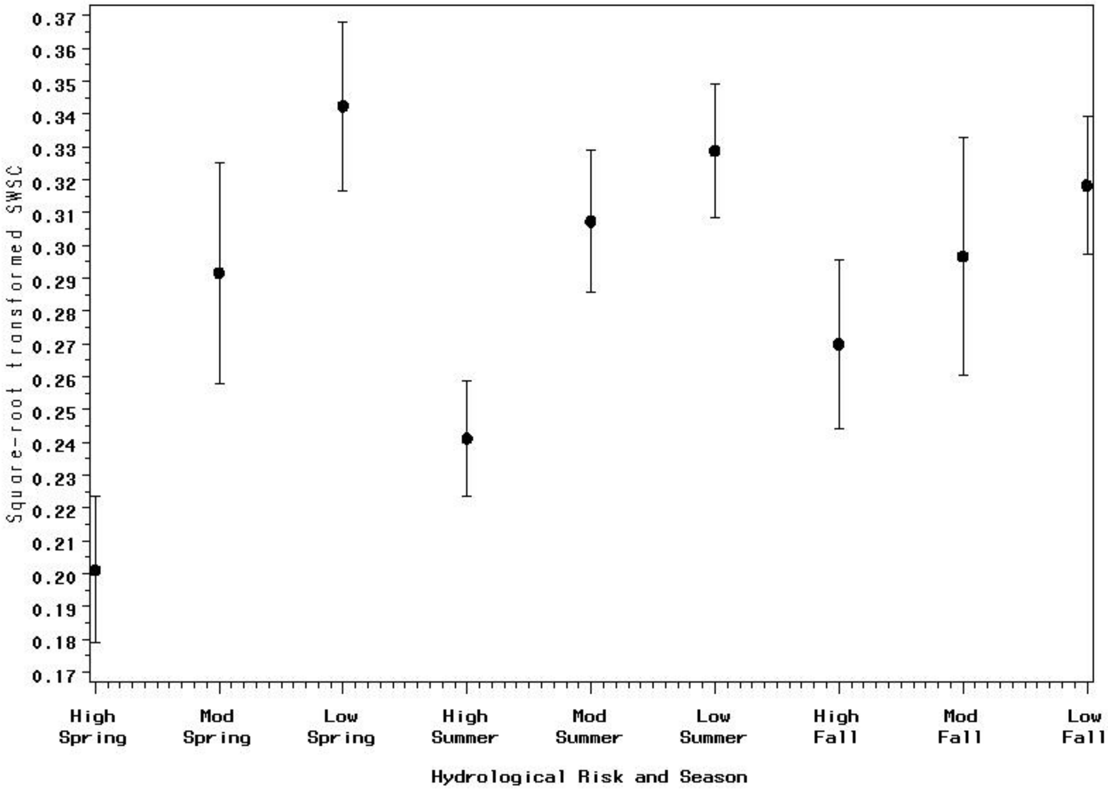


Figure 25. Least square mean estimates of square root transformed SWSC (circles) within watershed risk class and seasons in 2007, (error bars represent 95% CI, n=295).

4 Summary and recommendations

This project was initiated to address concerns about ground conditions affecting salvage harvesting, but it also provided insight as to the effect of the MPB infestation and salvage harvesting on soil hydrology. A decision support tool that enabled the broad-scale assessment of existing hydrologic conditions in the VFD was developed. The observations gathered during this investigation, and the management recommendations that follow, are designed to aid forest managers dealing with the MPB epidemic in the VFD and other forest districts. The list of indicators identified by this research and the model developed herein can be used for predictive mapping and operations management at the watershed and site levels.

Wet-ground areas identified in the VFD during this project were found to be associated with MPB-affected forest stands. The distribution of these locations was due to a combination of climate, the beetle infestation, and watershed physiographic conditions including slope and soil type. Climate, particularly precipitation levels in winter and summer, was found to have the most significant effect on soil moisture conditions in the forest district. Wet-ground areas were observed during wetter periods in those watersheds that have pre-existing conditions such as a lack of understorey and/or restricting soil layers that make them prone to losing summer ground. Wet-ground areas are not solely a function of canopy loss due to the MPB infestation; rather, they are a cumulative response to a number of factors that enhance delivery of precipitation to the ground and its retention within the soil profile. Salvage logging can contribute to expanding wet-ground area through canopy removal and soil disturbance effects on natural surface-drainage patterns.

The *post-hoc* assessment risk model effectively predicted field conditions at the 17 sites inventoried during the 2006 and 2007 sampling program. As such, its application is recommended for planning foresters as a tool for identifying those watersheds in the VFD, where operational issues with wet ground such as movement of harvesting equipment or vehicles and soil disturbance may be encountered. The model may be effective in other districts as well, given that the parameters chosen are general and use data that should be broadly available. However, it is recommended that field verification be completed to ensure the model's effectiveness in other districts.

During this investigation, it was found that the most effective indicators for predicting the risk of wet-ground areas at the watershed level were lodgepole pine content, understorey, drainage density, sensitive soils, and the topographic index. The information needed to quantify these variables is available from provincial databases. Lodgepole pine content is available from the B.C. Vegetation Resources Inventory dataset, understorey score is based on BEC information and understorey surveys provided by Coates et al. (2006) and Vyse et al. (2007), drainage density information is gathered from the watershed atlas, sensitive soils from soil and landform maps, and the topographic index by calculation using data from the watershed atlas.

5 Recommendations to forest managers:

- Use and verify the *post-hoc* model in other districts.
- Use risk map of summer-ground loss for operational planning (VFD only).
- Avoid sensitive soils during harvesting and road construction as much as possible by delineating sensitive areas on soil and landform maps during planning activities.
- Avoid salvage operations and site preparation activities on toe-slope areas during spring, summer and fall months because they are generally wet areas.

- Protect regeneration and lesser vegetation to maximise interception and evapotranspiration in salvage areas. In the absence of understorey, logging slash left at the stump or spread back out in the cutblock area would help increase interception.
- Use low ground pressure equipment or high flotation tires where required to maintain natural surface-drainage patterns to reduce disturbance effects that can exacerbate drainage problems and increase the risk of losing summer ground.
- Maintain natural drainage patterns during salvage operations. Where possible plan the road network ahead of time to minimize the number of stream crossings and try not to expose seepage areas.

The information provided here represents some of the first field observations on soil hydrology conditions in a MPB-affected district. Although these data are preliminary, they indicate that watering-up is not occurring in every watershed. In addition, they show that where watering-up does occur, water table levels can increase in the toe-slope and upslope positions. Further, the data demonstrate a need for further investigation into the role of the understorey and beetle-affected stands in net precipitation and soil water balance at the stand level.

6 Acknowledgements

We are grateful to Philip Krauskopf, Maria Saraiva, Megan Campbell, and Cindy Chevalier for assisting in site establishment, field data collection, and probe calibration. We also thank Dr. Shannon Berch and Mr. Dave Maloney for their reviews and helpful comments.

This project was funded by the Government of Canada through the Federal Mountain Pine Beetle Program, a program administered by Natural Resources Canada, Canadian Forest Service. Publication does not necessarily signify that the contents of this report reflect the views or policies of Natural Resources Canada, Canadian Forest Service.

7 Contacts

John Rex, Regional Hydrologist
BC Ministry of Forests and Range
Stewardship Branch
Prince George, BC
250-565-6921
John.Rex@gov.bc.ca

Stéphane Dubé, Regional Soil Scientist
BC Ministry of Forests and Range
Stewardship Branch
Prince George, BC
250-565-4363
Stephane.Dube@gov.bc.ca

8 Literature Cited

Aust, W.M.; Reisinger, T.M.; Burger, J.A.; Stokes B.J. 1993. Soil physical and hydrological changes associated with logging a wet pine flat with wide-tired skidders. Southern Journal of Applied Forestry 17:22–25.

Bagarello, V.; Iovino, M.; Elrick, D. 2004. A simplified falling-head technique for rapid determination of field-saturated hydraulic conductivity. Soil Science Society of America Journal 68:66–73.

Ballard, T.M. 2000. Impacts of forest management on northern forest soils. Forest Ecology and Management 133(1–2):37–42.

Banner, A.; Mackenzie, W.; Haeussler, S.; Thomson, S.; Pojar, J.; Trowbridge, R. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. B.C. MOF, Victoria, B.C. Land Management Handbook No. 26.

Banner, A.; LePage, P.; Moran, J.; de Groot, A (eds). 2005. Hydrology and Biogeochemistry. *Pages* 19–28 *in* The Hyp3 Project: Pattern, Process, and Productivity in Hypermaritime Forests of Coastal British Columbia: A synthesis of 7-year results. B.C. Ministry of Forests, Victoria B.C. Special Report 10.

British Columbia Ministry of Environment. 2008. http://www.env.gov.bc.ca/rfc/river_forecast/graphs/swesumm.html (accessed 31-July-2009)

British Columbia Ministry of Forests (BCMoF). 2001a. Generic Forest Health Surveys Guidebook. 2nd ed. Forest Practices Branch, B.C. Ministry of Forests. Victoria, B.C. Forest Practices Code of British Columbia Guidebook. 72 pp.

British Columbia Ministry of Forests (BCMoF). 2001b. Soil conservation surveys guidebook. 2nd ed. Forest Practices Code of British Columbia Guidebook. B.C. Ministry of Forests, Forest Practices Branch, Victoria, BC. 63 pp.

British Columbia Ministry of Forests (BCMoF); British Columbia Ministry of Environment, Lands and Parks (BCMoE). 1998. Field manual for describing terrestrial ecosystems. Land Managemant Handbook No. 25, Province of British Columbia, 237 pp.

Berger, K.P.; Entekhabi, D. 2001. Basin hydrologic response relations to distributed physiographic descriptors and climate. Journal of Hydrology 247:169–182.

Bethalmy, N. 1975. A Colorado episode: Beetle epidemic, ghost forests, more streamflow. Northwest Science 49(2):95–105.

Bilby, R.E.; Sullivan, K; Duncan, S.H. 1989. Generation and fate of road surface sediment in forested watersheds in western Washington. Forest Sciences 35(2):453–468.

Blake, G.R.; Nelson, W.W.; Allmaras, R.R. 1976. Persistence of subsoil compaction in a Mollisol. Soil Science Society of America Journal 40:943–948.

Block, R.; Van Rees, K.C.J.; Pennock, D.J. 2002. Quantifying harvesting impacts using soil compaction and disturbance regimes at a landscape scale. Soil Science Society of America Journal 66:1669–1676.

Boon, S. 2007. Snow accumulation and ablation is a beetle-killed pine stand in Northern Interior British Columbia. B.C. Journal of Ecosystems Management 8(3):1–13.

Bosch, D.D.; West, L.T. 1998. Hydraulic conductivity variability for two sandy soils. Soil Science Society of America Journal 62:90–98.

Bulmer, C.E.; Krzic, M. 2003. Soil properties and lodgepole pine growth on rehabilitated landings in northeastern British Columbia. Canadian Journal of Soil Science 83:465–474.

Coates, D.K.; DeLong, C.; Burton, P.J.;Sachs, D.L. 2006. Report for the Chief Forester August 2006: Abundance of Secondary Structure in Lodgepole Pine Stands Affected by the Mountain Pine Beetle. http://www.for.gov.bc.ca/hfp/mountain_pine_beetle/stewardship/report.pdf (accessed 30-July-2009)

Cochran, W.G.; Cox, G.M. 1950. Experimental Designs. John Wiley & Sons, Inc., New York. 454 pp.

Constantz, J.; Herkelrath, W.N.; Murphy, F. 1988. Air encapsulation during infiltration. Soil Science Society of America Journal 52:10–16.
Culley, J.L.B. 1993. Density and Compressibility. *Pages* 529–539 *in* Soil sampling and methods of analysis. Carter, M.R. (ed). Lewis Publishers, Boca Raton, FL.
Czarnomski, N.M.; Moore, G.W.; Pypker, T.G.; Licata, J.; Bond, B.J. 2005. Precision and accuracy of three alternative, instruments for measuring soil water content in two forest soils of the Pacific Northwest. Canadian Journal of Forest Research 35:1867–1876.
Dingman, S.L. 2002. Physical Hydrology. 2nd Edition. Prentice Hall, Upper Saddle River, NJ. 646 pp.
Dubé, S. 1994. Watering-up after clearcutting on forested wetlands of the St Lawrence lowland. M.Sc. thesis. Faculté des Études Supérieures, Université Laval, Québec.
Dubé, S.; Plamondon, A.; Rothwell, R. 1995. Watering-up after clear-cutting on forested wetlands of the St. Lawrence lowland. Water Resources Research 31(7):1741–1750.
Dunne, T.; Leopold, L.B. 1978. Interception. *Pages* 83–94 *in* Water in Environmental Planning. W.H. Freeman, San Francisco, CA. 818 pp.
Environment Canada. 2008.
http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html (Accessed 30-July-2009)
Foord, V. 2008. Analysis of weather station data in the Vanderhoof area. Ministry of Forests and Range, NIFR, internal unpublished report. 10 pp.
Fu, G.; Chen, S.; Liu, C.; Sheppard, D. 2004. Hydro-climatic trends of the Yellow River Basin for the last 50 years. Climatic Change 65:149–178.
Gee, G.W.; Bauder, J.W. 1986. Particle-size analysis. *Pages* 383–411 *in* Methods of soil analysis. Part 1. 2nd Ed. Klute, A. (ed). Agronomy Monograph 9. ASA-SSSA, Madison, WI.
Groot, A. 1998. Physical effects of site disturbance on peatlands. Canadian Journal of Forest Research 78:45–50.
Hewlett, J.D. 1982. Principles of Forest Hydrology. The **University of Georgia Press**. Athens, GA. 183 pp.
Hillel, D. 1998. Environmental soil physics. Academic Press, Elsevier, USA. 771 pp.
Hjerdt, K.N.; McDonnell, J.J.; Seibert, J.; Rodhe, A. 2004. A new topographic index to quantify downslope controls on local drainage. Water Resources Research, 40, W05602 (doi:10.1029/2004WR003130)
Jones, J.A.; Swanson, F.J.; Wemple, B.C.; Snyder, K.U. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology 14(1):76–85.
Kalra, Y.P.; Maynard, D.G. 1991. Methods manual for forest soil and plant analysis. Forestry Canada, Northwest Region, Northern Forestry Centre. Information Report NOR-X-319. 116 pp.
Knight, D.H.; Fahey, T.J; Running, S.W. 1985. Water and nutrient outflow from contrasting lodgepole pine forests in Wyoming. Ecol. Mono. 55(1):29–48.
Knighton, D. 1998. Fluvial Forms and Processes: A New Perspective. A Hodder Arnold Publication. Oxford University Press, New York, NY. 383 pp.
Kutilek, M. 2004. Soil hydraulic properties as related to soil structure. Soil & Tillage Research 79:175–184.
Ladekarl, U.L.; Rasmussen, K.R..; Christense, S.; Jensen, K.H.; Hansen, B. 2005. Groundwater recharge and evapotranspiration for two natural ecosystems covered with oak and heather. Journal of Hydrology 300(1):76–99.
Manly, B.F.J. 1994. Mutivariate statistical methods. Chapman & Hall/CRC, New York, NY. 215 pp.
Manly, B.F.J. 2000. Statistics for Environmental Science and Management. Chapman & Hall/CRC, New York, NY. 336 pp.
McNabb, D.H.; Startsev, A.D.; Hguyen, H. 2001. Soil wetness and traffic level effects on bulk density and air-filled porosity of compacted boreal forest soils. Soil Science Society of America Journal 65:1238–1247.
Nachabe, M.; Masek, C.; Obeysekera, J. 2004. Observations and modeling of profile soil water storage above a shallow water table. Soil Science Society of America Journal 68:719–724.

Pennock, D.J.; Anderson, D.W.; de Jong, E. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma 64:1–19.
Plamondon, A.P. 1993. Influence de la coupe sur l'écoulement annuel, le debit de pointe et la qualité de l'eau. Centre de Recherche en Biologie Forestière, Univ. Laval, Min. For., Québec. 179 pp.
Potts, D.F. 1984. Hydrologic Impacts of a large-scale mountain pine beetle epidemic. Water Resources Bulletin 20(3):373–377.
Powers, R.F. 2002. Effects of soil disturbance on the fundamental, sustainable productivity of managed forests. U.S. Department of Agriculture, Forest Service. General Technical Report PSW-GTR-183:63–82.
Putz, G.; Burke, J.M.; Smith, D.W.; Chanasyk, D.S.; Prepas, E.E.; Mafumo, E. 2003. Modelling the effects of boreal forest landscape management upon streamflow and water quality: Basic concepts and considerations. Journal of Environmental Engineering and Science 2:S87–S101.
Reynolds, W.D. 1993. Saturated hydraulic conductivity: Field measurement. *Pages* 599–613 *in* Soil sampling and methods of analysis. Carter, M.R. (ed.). Lewis Publishers, Boca Raton, FL.
Reynolds, W.D.; Elrick D.E.; Topp,G.C. 1983. A re-examination of the constant head well permeameter method for measuring saturated hydraulic conductivity above the water table. Soil Science 136:250–268.
SAS Institute Inc. 2003. SAS/STATS® user's guide. Vol. 2. Version 8.2, SAS Institute Inc., Cary, NC.
Schmid, J.M.; Mata, S.A.;.Martinez, M.H.; Troendle, C.A. 1991. Net precipitation within small group infestations of the mountain pine beetle. U.S. Department of Agriculture, Forest Service. Rocky Mountain Forest and Range Experimental Station, Fort Collins, CO. Research Note RM-508.
Sharratt, B.S.; W.B. Voorhees, W.B; McIntosh G. 1997. Amelioration of soil compaction by freezing and thawing. *Pages* 182–188 *in* Proceedings of the International Symposium on Physics, Chemistry, and Ecology of Seasonally Frozen Soils. I.K. Iskandar, E.A. Wright, J.K. Radke, B.S. Sharratt, P.H. Groenevelt, and L.D Hinzman, (eds), 10–12 June 1997, Fairbanks, Alaska. 595 pp.
Soil Classification Working Group. 1998. The Canadian System of Soil Classification. Agriculture and Agri-Food Canada. Publication 1646 (Revised). 187 pp.
Sokal, R.R.; Rohlf, F.J. 1995. Biometry: the principles and practice of statistics in biological research. 3rd ed. W.H. Freeman and Co., New York. 887 pp.
Spittlehouse, D.L. 2002. Sap flow and transpiration of old lodgepole pine trees. *Pages* 123–124 *in* Proceedings of the 25th Conference on Agricultural and Forest Meterology, 20–24 May 2002, Norfolk, Virginia. Amercian Meterological Society, Boston, MA.
Startsev, A.D.; McNabb, D.H. 2000. Effects of skidding on forest soil infiltration in west-central Alberta. Canadian Journal of Soil Science 80:617–624.
Sun, G.; McNulty, S.G.; Shepard, J.P.; Amatya, D.M.; Riekerk, H.; Comeford, N.B.; Skaggs, W.; Swift Jr, L. 2001. Effects of timber management on the hydrology of wetland forests in the southern United States. Forest Ecology and Management 143:227–236.
Systat. 2004. Systat 11: Statistics III. Systat Software Incorporated. 636 pp.
Tiessen, H.; Moir, J.O. 1993. Total and organic carbon. *Pages* 187–199 *in*: Soil sampling and methods of analysis. Carter, M.R. (ed.). Lewis Publishers, Boca Raton, FL.
Tisdall, J.M.; Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. Journal of Soil Science 33:141–163.
Tokuchi, N.; Ohte, N.; Hobara, S.; Kim, S.J.; Masanori, K. 2004. Changes in biogeocemical cycling following forest defoliation by pine wilt disease in Kiryu experimental catchment in Japan. Hydrological Processes 18:2727–2736.
Tsegaye, T.D.; Tadesse, W.; Coleman, T.L.; Jackson, T.J.; Tewolde, H. 2004. Calibration and modification of impedance probe for near surface soil moisture measurements. Canadian Journal of Soil Science 84:237–243.

Vyse, A.C.; Roach, J.; Zimonick, B. 2007. Draft interim report. Regeneration beneath lodgepole pine dominated stands attacked or threatened by the mountain pine beetle in the Kamloops Timber Supply Area. Advanced Technology Centre. Thompson Rivers University, Kamloops, BC. 26 pp.

Ward, A.D.; Trimble, S.W. 2004. Environmental Hydrology. 2nd Ed. Lewis Publishers. CRC Press, Boca Raton, FL. 504 pp.

Weight, W.D.; Sonderegger, J.L. 2001. Manual of Applied Field Hydrogeology. McGraw- Hill, New York, NY. 632 pp.

Williamson, J.N.; Neilsen, W.A. 2000. The influence of forest site on rate and extent of soil compaction and profile disturbance of skid trails during ground-based harvesting. Canadian Journal of Forest Research 30:1196–1205.

Wuddivira, M.N.; Camps-Roach, G. 2007. Effects of organic matter and calcium on soil structural stability. European Journal of Soil Science 58:722–727.

Appendix 1: GIS Attributes and Analytical Processes

Attribute Description	Source(s)	Input Item	Output Item	Code Ref#	Analysis Notes	Type	Done
Agriculture Area (ha)	qbtm_dva	PLU_CLASS	AGRICAREA	7	Calculate in GRID	area	1
Area of complete watershed (ha)	wsa	AREA	WS_AREA	5	Calculate in GRID	area	1
Area of Pine >= Age Class 3 (ha)	vri	SPC1->6 & Projected Age Class	PINEAREA3	14b	Calculate in GRID	area	1
Area of Pine >Age Class 4 (ha)	vri	SPC1->6 & Projected Age Class	PINEAREA_GT4	14a	Calculate in GRID	area	1
Area of WS covered by PEM (DVA) (ha)	twsa_dva/dva_pem2	AREA	WS_IN_PEM_AREA	6	Calculate in GRID	area	1
Aspect	dva_pem2	SLP_ASP (3rd character)	ASPECT_CD	18/19	ZONALMAJORITY (WRAPARC2GRID.AML)	code	1
Beetle Attack 4 or more years	fhfp_2003_dva	CAPTURE_YE and PEST_SPECI	MPBOLDATTACKAREA	34	Calculate in GRID	area	1
Beetle Attack Severity (2004)	fhfp_2004_dva	SEVERITY and FHF	MPB_SEVERITY	12	Calculate in GRID	code	1
Biogeoclimatic Unit	abec_dva	BECLABEL	BECLABEL	18	ZONALMAJORITY (WRAPARC2GRID.AML)	code	1
Biogeoclimatic Unit (PEM)	dva_pem2	BGC_PEM	BGC_PEM	18	ZONALMAJORITY (WRAPARC2GRID.AML)	code	1
Channel Length - dry (km)	trim	LENGTH	DRY_STR_LENGTH	27	Calculate with INTERSECT/FREQUENCY	length	1
Channel Length - wet (km)	trim	LENGTH	WET_STR_LENGTH	25	Calculate with INTERSECT/FREQUENCY	length	1
Elevated Water Table Potential (pct)	dvasoil_fnl	VALUE	WS_SL_ELEVWT_PCT	SL 2.e	Calculate in GRID	percent	1
Erosion Potential (pct)	dvasoil_fnl	VALUE	WS_SL_EROS_PCT	SL 2.c	Calculate in GRID	percent	1
ESA Soils Area (ha)	fesa_dva	ISESASOIL	ESA_SOIL_AREA	35	Calculate in GRID	area	1
ESA Soils Percent	fesa_dva	ISESASOIL	ESA_SOIL_PCT	35	Calculate in GRID	percent	1
Forest Cover	vri	INVENTORY_TYPE_GROUP_NUM	ITG	13	Calculate in GRID	code	1
Forested Area (ha)	vri	PROJ_TYPE_ID	FORESTAREA	15	Calculate in GRID	area	1
Harvested Forest Area (ha)	fdp/vri	ISLOGGED	LOGAREA	9	Calculate in GRID	area	1
Length of dry stream harvested (km)	fdp/vri & trim	LENGTH	DRY_LOG_LENGTH	31	Calculate with INTERSECT/FREQUENCY	length	1
Length of wet stream harvested (km)	fdp/vri & trim	LENGTH	WET_LOG_LENGTH	31	Calculate with INTERSECT/FREQUENCY	length	1
Organic Areas (pct)	dvasoil_fnl	VALUE	WS_SL_ORG_PCT	SL 2.d	Calculate in GRID	percent	1
Percent of dry stream harvested (km)	fdp/vri & trim	LENGTH	DRY_LOG_PCT	31	Calculate in TABLES	percent	1
Percent of wet stream harvested (km)	fdp/vri & trim	LENGTH	WET_LOG_PCT	31	Calculate in TABLES	percent	1
Number of Stream Crossings - dry	trim and ften	FREQUENCY	DRY_CROSSINGS	30	BUFFER, INTERSECT, RESELECT, DELETE ARCS, BUILD POINT COVER, INTERSECT/FREQUENCY	point count	1
Number of Stream Crossings - wet	trim and ften	FREQUENCY	WET_CROSSINGS	30	BUFFER, INTERSECT, RESELECT, DELETE ARCS, BUILD POINT COVER, INTERSECT/FREQUENCY	point count	1
Percent of steep areas (>20%) (ha)	tdem_dva		WS_SLP20_PCT	11	Calculate in GRID	percent	1
Percent of watershed within DVA	twsa_dva	AREA	WS_IN_DVA_PCT	5	Calculate in GRID	percent	1
Percent of WS covered by PEM	twsa_dva/dva_pem2	AREA	WS_IN_PEM_PCT	6	Calculate in GRID	percent	1
Projected Harvesting Area (ha)	fdp/vri	ISPLANNED	PROJLOGAREA	10	Calculate in GRID	area	1
Protected Areas (ha)	aprk_dva	APRK_DVA#	PROTECTED_AREA	20	Calculate in GRID	area	1
Road Length (km)	trim and ften	LENGTH	RD_LENGTH	29	Calculate with INTERSECT/FREQUENCY	length	1
Site and Soil Features 1 (ha) *	dva_pem2	SITESOIL1	SITESOIL1AREA	16	Calculate in GRID	area	1
Site and Soil Features 2 (ha)	dva_pem2	SITESOIL2	SITESOIL2AREA	16	Calculate in GRID	area	1
Slope	dva_pem2	SLP_ASP (1st and 2nd character)	SLOPE_CD	18/19	ZONALMAJORITY (WRAPARC2GRID.AML)	code	1
Soil Depth and Texture (ha)	dva_pem2					area	
Soil Moisture	dva_pem2	SMR_PEM2	SMR_PEM2	33	Calculate in GRID	code	1
Soil Nutrient	dva_pem2	SNR_PEM2	SNR_PEM2	33	Calculate in GRID	code	1
Special Sites (ha)	dva_pem2	SPECIAL_PE	SPECIALAREA	17	Calculate in GRID	area	1
Stream order	twsa_dva	WSA_ORDER		na	PAT item	code	1
Sufficiently Restocked (ha)	vri	SILV_BASE/PROJ_TYPE_ID	STOCKEDAREA	32	Calculate in GRID	area	1
Urban Area (ha)	qbtm_dva	PLU_CLASS	URBANAREA	8	Calculate in GRID	area	1
Watershed Code	twsa_dva	WATERSHED_CD		na	PAT item	code	1
Watershed Name	WsBC	NAME	NAME	4	Relate to WsBC data	code	1
Watersheds BC key	watlite_dva	ID_WATLITE	ID_WATLITE	3	Primary key to WsBC data files	code	1

Site Series	dva_pem2	SITE_S1			Separate table produced from vector overlay of PEM and watersheds		

* Note one poly with "G" value instead of "g" - fixed manually

Appendix 2: Soil Pit Description

Table A1. Morphological description of Orthic Dystric Brunisol pedon, Angly Lake

Horizon	Depth (cm)	Description
Ln	6–3	Weak, compact matted, resilient, mossy; plentiful fine roots; common fungal mycelia; few fecal droppings.
Fm	3–0	Strong (check), non-compact matted, pliable, fibrous; abundant fine roots and few medium roots; common fungal mycelia, few fecal droppings.
Ahe	0–2	Dark brown (7.5YR 3/2 m); silt; fine granular; plentiful very fine roots; moderately porous; 0% coarse fragments.
Bf	2–10	Dark brown (7.5YR 4/3 m); silt loam; fine granular; plentiful fine roots and few coarse roots; moderately porous; 5% subrounded and subangular gravels.
Bm	10–22	Dark yellowish brown (10YR 4/4 m); silt loam; fine granular; plentiful fine roots and few coarse roots; moderately porous; 20% subrounded and subangular gravels, 5% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.
C	22–53+	Grayish brown (10YR 5/2 m); silt; very fine subangular blocky; few medium roots; slightly porous; 25% angular cobbles, 50% angular stones and boulders.

Table A2. Morphological description of Orthic Humo-Ferric Podzolic pedon, Cobb Lake

Horizon	Depth (cm)	Description
Ln	8–5	Weak, non-compact matted, loose, mossy; few fine roots.
Fa	5–0	Moderate, non-compact matted, resilient (check), felty, fibrous; plentiful very fine and fine roots; common fungal mycelia; few fecal droppings; few earthworms.
Ae	0–4	Dark greyish brown (10YR 4/2 m); loam; fine granular; plentiful very fine and coarse roots; moderately porous; 35% subrounded and subangular gravels.
Bf	4–17	Dark yellowish brown (10YR 3/6 m); silt loam; very fine angular blocky; plentiful fine, medium, and coarse roots; highly porous; 25% subrounded and subangular gravels, 10% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.
BC	17–45	Weak red (2.5YR 4/2 m); sandy loam; fine angular blocky; plentiful very fine and fine roots; highly porous; 25% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
C	45+	Dark greyish brown (10YR 4/2 m); loamy sand; single grained; plentiful medium roots and few fine roots; highly porous; 30% subrounded and subangular gravels, 5-% subrounded and subangular cobbles.

Table A3. Morphological description of Orthic Gray Luvisol pedon, Belisle

Horizon	Depth (cm)	Description
Lv	6–5	Moderate, non-compact matted, friable, acerose, leafy; few very fine roots.
Fa	5–1	Moderate, compact matted, resilient, mossy, fibrous; abundant very fine roots and few fine roots; common fungal mycelia; few fecal droppings.
Hh	1–0	Greasy.
Ah	0–4	Brown (7.5YR 4/3 m); silt loam; medium granular; plentiful fine and coarse roots; highly porous; 0% coarse fragments.
Bt	4–52	Brown (10YR 4/3 m); silty clay; medium subangular blocky; few fine and coarse roots; moderately porous; 5% subrounded and subangular gravels.
C	52+	Light brownish gray (10YR 6/2 m); sandy loam; medium platy; no roots; slightly porous; 20% subrounded and subangular gravels, 5% subrounded and subangular cobbles.

Table A4. Morphological description of Orthic Dystric Brunisol pedon, Pitka

Horizon	Depth (cm)	Description
Ln	7–5	Weak, non-compact matted, loose, acerose.
Fm	5–0	Moderate, compact matted, resilient, fibrous; plentiful fine and medium roots; common fungal mycelia; few fecal droppings.
Ae	0–1	Brown (7.5YR 4/2 m); silt loam; very fine subangular blocky; few very fine and fine roots; highly porous; 10% subrounded and subangular gravels.
Bm	1–29	Dark yellowish brown (10YR 3/4 m); loam; fine subangular blocky; plentiful fine and medium roots; highly porous; 30% subrounded and subangular gravels, 15% subrounded and subangular cobbles, charcoal present at 26 cm.
BC	29–73	Dark grayish brown (10YR 4/2 m); loam; common, medium, faint mottles; fine subangular blocky; plentiful fine roots and few coarse roots; moderately porous; 40% subrounded and subangular gravels, 10% subrounded and subangular cobbles, 10% subrounded and subangular stones and boulders.
C	73+	Dark grayish brown (10YR 4/2 m); loam; common, medium, faint mottles; medium platy; few very fine roots; slightly porous; 20% subrounded and subangular gravels, 10% subrounded and subangular cobbles.

Table A5. Morphological description of Eluviated Dystric Brunisol pedon, Peta

Horizon	Depth (cm)	Description
Ln	5–2	Weak, non-compact matted, resilient, mossy; plentiful fine roots and few medium roots; few fungal mycelia; few fecal droppings.
Fm	2–0	Moderate, compact matted, tenacious, felty; common fungal mycelia; few beetle larvae and nematodes.
Aej	0–2	Pale brown (10YR 6/3 d) to brown (10YR 5/3 m); sandy loam; single grained; few very fine roots; 20% subrounded and subangular gravels.
Bm1	2–19	Brown (7.5YR 4/3 d); sandy loam; medium granular; plentiful fine roots and few medium roots; highly porous; 40% subrounded and subangular gravels, 5% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.
Bm2	19–42	Dark grayish brown (10YR 4/2 d); loamy sand; single grained; plentiful fine roots and few medium roots; highly porous; 35% subrounded and subangular gravels, 10% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.
Cg	42–69	Brown (10YR 5/3 d); fine sandy loam; many, medium, prominent yellowish red (5YR 4/6 m) mottles; medium granular; few fine and very fine roots; moderately porous; 15% subrounded and subangular gravels.
Cgc	69+	Brown (10YR 5/3 d); fine sandy loam; many, medium, prominent yellowish red (5YR 4/6 m) mottles; fine subangular blocky; no roots; slightly porous; 15% subrounded and subangular gravels.

Table A6. Morphological description of Orthic Humo-Ferric Podzolic pedon, Crystal Lake

Horizon	Depth (cm)	Description
Lv	6–4	Weak, non-compact matted, pliable, mossy; abundant fine roots and plentiful fine roots; few fecal droppings.
Fa	4–0	Moderate, non-compact matted and granular, friable, greasy; abundant very fine roots and plentiful medium roots; common fungal mycelia; common fecal droppings; very abundant earthworms.
Hh	<1	Discontinuous.
Ae	0–2	Brown (7.5YR 4/2 m); silt loam; fine subangular blocky; few fine and medium roots; highly porous; 20% subrounded and subangular gravels.
Bf	2–20	Dark yellowish brown (10YR 3/4 m); loam; fine subangular blocky; few medium roots and plentiful coarse roots; highly porous; 15% subrounded and subangular gravels, 5% subrounded and subangular cobbles.
BC	20–93	Grayish brown (10YR 5/2 m); fine sandy loam; fine angular blocky; plentiful medium roots and few very fine roots; highly porous; 15% subrounded and subangular gravels, 5% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.
C	93+	Grayish brown (10YR 5/2 m); fine sandy loam; common, medium, distinct mottles; fine subangular blocky; no roots; moderately porous; 30% subrounded and subangular gravels.

Table A7. Morphological description of Orthic Dystric Brunisol pedon, Moosebone

Horizon	Depth (cm)	Description
Ln	8–4	Weak, non-compact matted, loose, mossy; plentiful medium roots and few fine roots.
Fa	4–0	Moderate, non-compact matted, pliable, fibrous; abundant very fine roots and plentiful fine roots; few fungal mycelia; few fecal droppings; few centipedes, plentiful earthworms.
Ahe	0–1	Brown (7.5YR 5/2 m); loam; very fine angular blocky; plentiful very fine roots and few medium roots; highly porous; 25% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
Bm1	1–12	Brown (7.5YR 4/2 m); loam; very fine subangular blocky; plentiful fine roots and few coarse roots; highly porous; 35% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
Bm2	12–26	Dark grayish brown (10YR 4/2 m) sandy loam; many, medium, distinct mottles; fine angular blocky; plentiful medium roots and few very fine roots; highly porous; 35% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
C	26+	Grayish brown (10YR 5/2 m); sandy loam; many, medium, faint strong brown (7.5YR 5/6 m) mottles; very fine angular blocky; compacted beginning at 69 cm; few very fine and fine roots; moderately porous; 30% subrounded and subangular gravels, 20% subrounded and subangular cobbles, 5% subrounded and subangular stones and boulders.

Table A8. Morphological description of Orthic Dystric Brunisol pedon, Chowsunkut;

Horizon	Depth (cm)	Description
Ln	6–3	Weak, non-compact, matted, resilient, mossy.
Fa	3–0	Moderate, non-compact matted, friable, felty, acerose; abundant fine roots and plentiful very fine roots; common fecal mycelia; few fecal droppings.
Aej	0–1	Brown (7.5YR 4/2 m); silt loam; very fine angular blocky; plentiful medium roots and few fine roots; moderately porous; 10% subrounded and subangular gravels, 15% subrounded and subangular cobbles, 15% subrounded and subangular stones and boulders.
Bm1	1–21	Brown (7.5YR 4/3 m); sandy loam; very fine angular blocky; plentiful very fine and medium roots; highly porous; 35% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
Bm2	21–36	Brown (10YR 4/3 m); loamy sand; single grained; plentiful fine roots and few medium roots; highly porous; 55% subrounded and subangular gravels, 10% subrounded and subangular cobbles.
Bmj	36–51	Grayish brown (10YR 5/2 m); fine sandy loam; many, fine, distinct mottles; fine prismatic; few very fine roots; moderately porous; 10% subrounded and subangular gravels.
C	51+	Dark grayish brown (10YR 4/2 M); loam; common, fine, distinct mottles; fine angular blocky; compacted beginning at 64 cm; few very fine roots; slightly porous; 40% subrounded and subangular gravels, 5% subrounded and subangular cobbles, 30% subrounded and subangular stones and boulders.

Table A9. Morphological description of Orthic Humo-Ferric Podzol pedon, 10426 Spot Check Site

Horizon	Depth (cm)	Description
Ln	5–3	Weak, blocky, loose, acerose; few fine roots.
Fa	3–0	Moderate, non-compact matted. Pliable, fibrous, greasy; plentiful fine and medium roots; common fungal mycelia.
H	<1	
Ae	0–2	Brown (7.5YR 4/2 m); silt; very fine angular blocky; plentiful very fine and medium roots; moderately porous; 5% subrounded and subangular gravels, 20% subrounded and subangular cobbles.
Bf	2–14	Dark yellowish brown (10YR 3/4 m); silt; very fine angular blocky; plentiful very fine and medium roots; moderately porous; 10% subrounded and subangular gravels, 10% subrounded and subangular cobbles, 15% subrounded and subangular stones and boulders.
B	14–47	Brown (7.5YR m); silt loam; fine angular blocky; plentiful fine and medium roots; moderately porous; 15% subrounded and subangular gravels, 5% subrounded and subangular cobbles, 20% subrounded and subangular stones and boulders.
C	47+	Brown (7.5YR m); silt loam; many, fine, distinct, mottles; very fine angular blocky; no roots; slightly porous; 10% subrounded and subangular gravels, 10% subrounded and subangular cobbles, 10% subrounded and subangular stones and boulders.

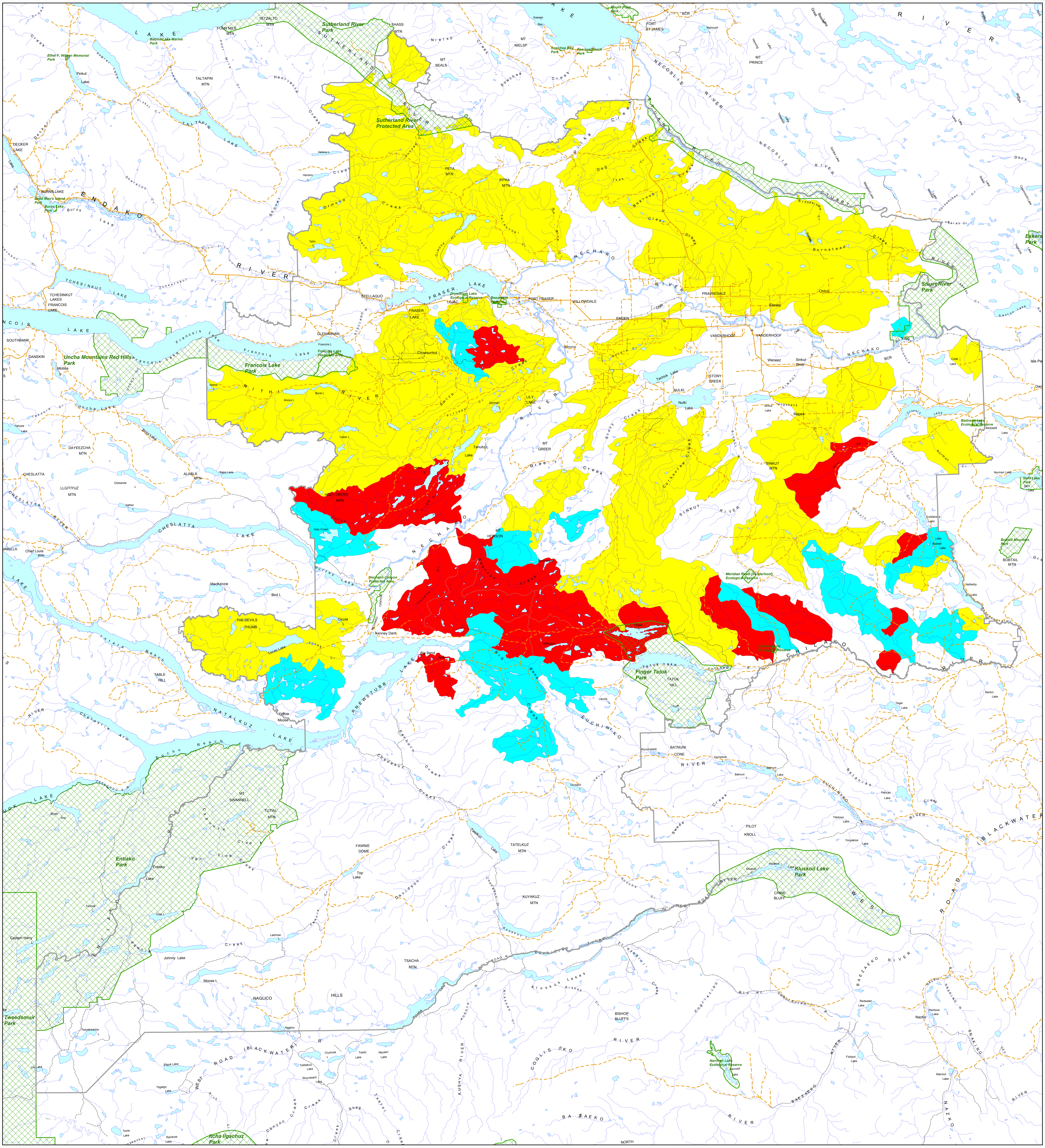
Table A10. Morphological description of Orthic Gleysol pedon, 10557 Spot Check Site

Horizon	Depth (cm)	Description
Ln	5–3	Weak, non-compact matted, loose, acerose, mossy; few very fine roots.
Fz	3–0	Moderate, non-compact matted, friable, fibrous; plentiful fine and moderate roots.
H	<1	Charcoal fragments throughout.
Aej	0–1	Silt.
Bmj	1–6	Brown (7.5YR 4/3 m); silt; fine angular blocky; plentiful very fine and medium roots; moderately porous; 10% subrounded and subangular gravels, 5% subrounded and subangular cobbles.
Bg1	6–18	Gray (10YR 5/1 m); silt; common, medium, prominent mottles; medium angular blocky; plentiful medium roots and few fine roots; moderately porous; 5% subrounded and subangular gravels, 5% subrounded and subangular cobbles.
Bg2	18–41	Grayish brown (10YR 5/2 m); silt; many, fine, distinct mottles; fine angular blocky; few medium roots; moderately porous; 15% subrounded and subangular gravels, 5% subrounded and subangular cobbles.
Bg3	41–46	Gray (7.5 YR m); silt; common, medium, distinct mottles; medium angular blocky; no roots; slightly porous; 5% subrounded and subangular gravels, 5% subrounded and subangular cobbles.
Cg	46+	Dark grayish brown (10YR 4/2); silty clay loam; common, medium, distinct mottles; massive; no roots; slightly porous; 20% subrounded and subangular gravels, 5% subrounded and subangular cobbles.

Appendix 3: Risk of Summer-ground Loss in VFD Watersheds

Vanderhoof Forest District

Third and Fourth Order Watershed Ranking



Legend

Administrative Boundaries
- Vanderhoof Forest District
- Parks and Protected Areas

Transportation Features
- Paved Road
- Gravel Road
- Trail
- Bridge
- Railway

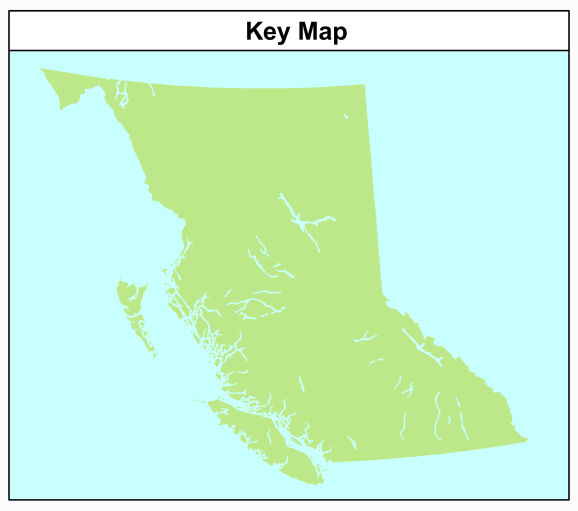
Contours (100 metre interval)
- Index Contour
- Interval Contour

1:200,000

6 3 0 6 12 18 24

Kilometers

Key Map



Data Sources and Notes

Watersheds:
3rd and 4th order watershed boundaries from provincial watershed atlas

Parks and Protected Areas:
Provincal protected areas boundaries for all protected areas designated by OIC or legislation.

Base Map:
1:250,000 Digital Baseline Mapping (NTS)

Contours:
1:20,000 TRIM contours at 100 metre intervals (selected from LRDW WHSE_BASEMAPPING.TRIM_CONTOUR_LINES; recoded index and interval contours)

Disclaimer:
This map is a visual representation and is not to be used for legal purposes.

N W E S

Produced for:

Ministry of Forests

Produced by:

British Columbia

Ministry of Sustainable Resource Management
Land Information BC

Projection/Datum: Albers Equal Area Conic (BC Albers)/NAD 1983
Created by: Prince George Contact Centre, kjb
W:\srm\prg\Workarea\sbarry\p05_1003_dva_mpb_watershed\maps\dva_ws_rank_200k_032009_sean.mxd
March 20, 2009