Streamline

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Peer-reviewed Research Article

Alberta's Southern Rockies Watershed Project—How Wildfire and Salvage Logging Affect Water Quality and Aquatic Ecology

Uldis Silins, Kevin D. Bladon, Axel Anderson, John Diiwu, Monica B. Emelko, Michael Stone, and Sarah Boon

The eastern slopes of Alberta's Rocky Mountains produce the vast majority of surface water supplies in the central and southern regions of the province. Population growth, industrial development, and agricultural expansion over the past two decades have dramatically increased water demand in this region. Such pressures on water resources, along with the rapid expansion of urban development into wildland areas, heavy recreational use, and public concerns over the impacts of climate change have led to a substantial increase in attention on headwater or source water protection issues in Alberta's eastern-slope forests. This new focus has created fundamental challenges for forest watershed and integrated water managers in Alberta and many other regions of North America.

Natural disturbance from wildfire and forest pest/disease outbreaks has been a common historic feature of Alberta's forested landscape. A series of unusually large and severe wildfires in the last decade, along with the recent appearance of large-scale mountain pine beetle (MPB) outbreaks beginning in 2004/05, have raised new concerns over climate change impacts on the frequency and severity of large-scale natural disturbances. The Lost Creek wildfire in the Crowsnest Pass was one of the first in a series of large wildfires in southwest Alberta and southeast British Columbia during the 2003 fire season. The wildfire burned out of control for 26 days and consumed over 21 000 ha in the headwaters of the Oldman River Basin, threatening wildlife, industry, and communities. The wildfire was unusually severe because of very dry conditions and high fuel loads, and burned as a nearly contiguous crown fire that consumed virtually all of the forest floor across extensive regions within the burn boundary (Figure 1).

The Southern Rockies Watershed Project (SRWP) was established in response to the need for information on how severe wildfire disturbance (including incremental effects of salvage logging) affects a range of "watershed values." The objectives of SRWP were to describe the immediate impacts of the wildfire on the hydrology, water quality, and aquatic ecology of disturbed watersheds and to assess the early trajectory of watershed recovery in subsequent years. To date, SRWP has produced one of the most comprehensive datasets describing both the basic hydrology

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and the impacts of severe natural disturbance on a range of watershed values in the high water-yielding, source watersheds of Alberta's Rocky Mountains (eastern slopes). The purpose of this article is to introduce this project by briefly summarizing the scope of research underway at the study area and by highlighting a small subset of results that focus on key indicators of water quality and stream health (ecologic response).

Study Description

Research watersheds were established in the winter of 2003/04 to capture data from the first post-disturbance hydrologic events during the spring snowmelt of 2004. Seven watersheds were instrumented to enable automated and manual hydrometric, water quality, and stream ecological monitoring. Instrumentation was installed in three burned watersheds (Lynx, Drum, and South York Creeks), two

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Figure 1. High fire severity in Lynx Creek. Note the loss of forest floor.

Table 1. Annual precipitation (mm) in the study watersheds during 2004-2007

Watershed	Year				
	2004	2005	2006	2007	Mean
Unburned (Reference)					
Star	1138	1182	737	699	939
North York	1390	1460	1007	1056	1228
Burned					
South York	1227	1471	1203	1185	1271
Lynx	1351	1717	1025	1079	1293
Drum	740	1177	782	631	832
Burned and Salvage Logged					
Lyons East	-	1111	996	668	925
Lyons West	-	1084	1039	655	926

post-fire salvage-logged watersheds (Lyons West and Lyons East Creeks), and two unburned (reference) watersheds (Star and North York Creeks). A well-distributed network of 15 climate stations provides continuous data for precipitation, air and ground temperature, relative humidity, radiation, snowpack depth, and wind speed (Figure 1).

Study watersheds range in size from 360–1315 ha (830 ha mean) with an average elevation of 1800 m (Figure 2). The proportion of total watershed area burned in the five disturbed watersheds ranges from 53 to 100%; however, this proportion includes alpine areas that did not burn because of a lack of tree cover. Virtually all forested stands in the burned catchments were consumed by the fire. Salvage operations occurred on 63% of the burned area in Lyons Creek West (40% of the total watershed area harvested) and 22% of the burned area in Lyons Creek East (18% of the total watershed area harvested).

The region encompassed by the study is broadly characteristic of Rocky Mountain front-range physiographic settings, with all watersheds spanning upper Montane, Subalpine, and Alpine ecozones. Lodgepole pine (*Pinus contorta* var. *latifolia*), Engelmann spruce (*Picea engelmanii*), and subalpine fir (*Abies lasiocarpa*) are the dominant tree species, occurring in pure and mixed stands at ecozone transitional areas. The study area is also in one of the highest water-yielding regions of Alberta, with mean annual precipitation (2004 to 2007) across the seven watersheds of

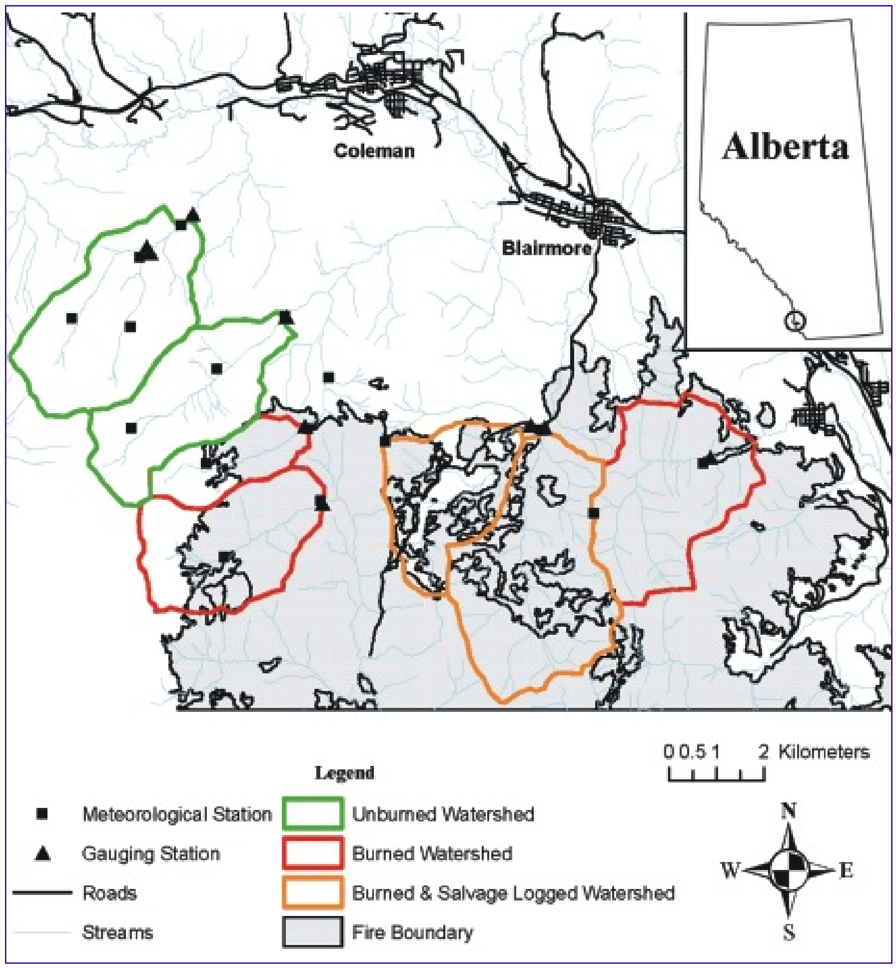

Figure 2. Southern Rockies Watershed Project map with the 2003 Lost Creek wildfire boundary, meteorological stations, streamflow gauging stations, and study watersheds (From West to East: Star, North York, South York, Lynx, Lyons West, Lyons East, and Drum Creeks).

1060 mm (range: 630–1720 mm) (Table 1). The majority (50 to 70%) of total annual precipitation falls as snow from October to April.

The streamflow regime is snowmelt-dominated with peak streamflow usually occurring during the period of snowpack melt in mid to late May. The region also receives significant early- and mid-summer rains, which can produce large flow events. This distinguishes this region from British Columbia's East Kootenays, where both summer precipitation and

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summer baseflows are lower. While the study area is geographically close to the East Kootenay region, subtle differences in climate produce important differences in regional hydrology. Both regions experience their lowest streamflows in August.

Streamflow is monitored continuously in all watersheds with pressure transducers and gas bubblers that use stage-discharge relationships at natural control sections. In addition to the seven main study catchments, six nested sub-watersheds are gauged within the two reference watersheds. Mean annual streamflow across all seven watersheds during the study period ranged from 380 to 1250 mm/year. The groundwater hydraulic gradients are strong throughout the study area, because of the steep physiography. Mean area-weighted catchment slopes range from 24.8 to

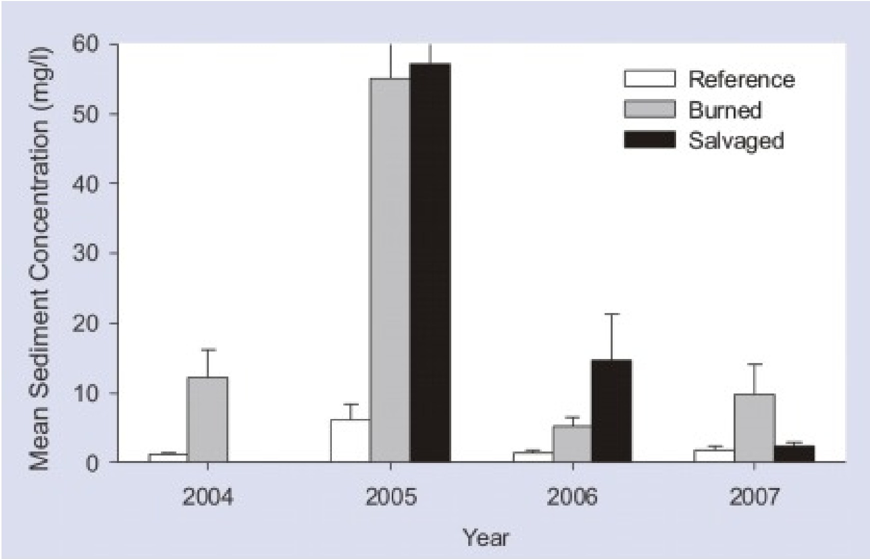

Figure 3. A comparison of the mean total suspended sediment concentration (mg/l) following the 2003 Lost Creek wildfire between reference, burned, and post-fire salvage-logged watersheds from 2004 to 2007 (adapted from Silins et al. 2009). Bars indicate the standard error of the mean.

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Figure 4. Streambank slumping in Lyons Creek East 2005 (1 year after the fire).

48.8%. Qualitatively, it is evident that groundwater contributions are significant for all study streams. Given this contribution, surface streams generally flow all year, allowing year-round monitoring of the 13 hydrometric gauging stations.

In addition to baseline monitoring of climatic variables and stream discharge, insights into the impacts of wildfire on precipitation inputs to the burned landscape are provided by annual snowpack surveys and measurements of rainfall interception (throughfall and stemflow) in burned and reference stands.

Water quality monitoring is ongoing in each of the seven watersheds using a comprehensive four-stage sampling approach.

1. Water temperature, dissolved oxygen (DO), electrical conductivity, pH, redox potential (ORP), turbidity, and salinity are monitored continuously during ice-free periods using automated water quality Sondes (YSI 6820/6920).
2. Daily water samples are collected for sediment concentration and turbidity using automated samplers (ISCO 6712 Series) during the ice-free period from May to September.
3. Routine sampling for nutrients and major cations/anions is conducted every 10 days during snowmelt freshet, every 14 days after the freshet (i.e., ice-free periods), and every 1 to 2 months during winter. Analyses include total nitrogen (TN), total dissolved nitrogen (TDN), ammonium (NH_4^+), nitrate (NO_3^-), total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), potassium (K^+), sulphate (SO_4^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), iron (Fe^{2+}), aluminum (Al^{3+}), chloride (Cl^-), silica, dissolved organic carbon (DOC), and dissolved and suspended solids.
4. Sampling for a full-suite metals analysis (US EPA metals) occurs two to three times each year under a range of flow conditions (snowmelt, stormflow, and baseflows). Oxygen isotope samples from precipitation and surface streams are also collected in all seven watersheds throughout the study. These samples may be used to provide insight into the relative surface/groundwater components that contribute to overall streamflow.

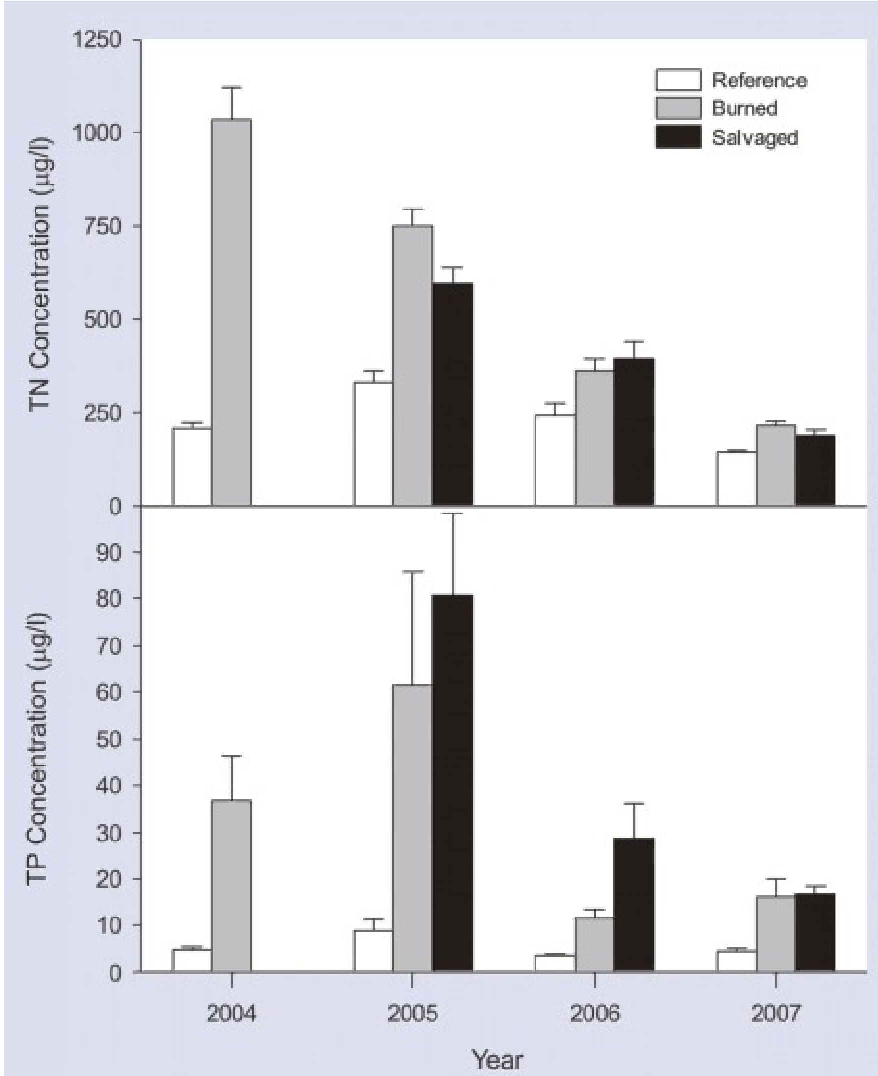

Figure 5. Mean total nitrogen (TN) and total phosphorus (TP) concentrations (µg/l) following the 2003 Lost Creek wildfire in reference, burned, and post-fire salvage-logged watersheds from 2004 to 2007 (adapted from Bladon et al. 2008 and Silins et al. in review). Bars indicate the standard error of the mean.

Ecological responses to wildfire and post-fire salvage logging are being assessed through studies of stream algal growth and benthic macroinvertebrate community response. Algal production is measured in all watersheds by periodic sampling from artificial streambed substrates (replicate unglazed porcelain tiles). Samples are collected monthly (May to October) for fluorometric analysis of chlorophyll *a* (Chl*a*) and determination of ash free dry mass (AFDM).

Samples of benthic macroinvertebrates are collected (Surber sampler) and identified to the lowest possible taxonomic grouping (usually family) and assigned to a functional feeding group (filterer, shredder, scraper, or predator). Stable isotope analysis (SIA) is then conducted for carbon (^{13}C) and nitrogen (^{15}N) to provide an indication of the overall stream ecosystem response to disturbance (wildfire and salvage logging) and evidence of changes in the structure of stream food webs (autochthonous versus

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allocthonous food sources) between the watersheds.

Water Quality Response

Only selected water quality parameters are presented here due to the large number of chemical water quality parameters measured in this study. Total suspended sediment (TSS) concentration was strongly affected by both the wildfire and salvage logging, and the magnitude of these effects varied with time after the wildfire (Figure 3). TSS concentrations across the 4 post-fire years were eight times greater in the burned and nine times greater in the salvage-logged watersheds compared to the reference watersheds (Silins et al. 2009). While the results for disturbed watersheds were significantly different than results for the reference watersheds, there were no differences in mean TSS concentrations between burned and post-fire salvage-logged watersheds during this same period. The largest differences in sediment production between undisturbed and disturbed landscapes were observed during both the snowmelt freshet and periodic stormflows. The range of sediment concentration and production in burned watersheds was 6 to 15 times greater than in reference watersheds during higher flows (snowmelt freshet and stormflows). The additional disturbance from post-fire salvage logging produced considerably more sediment during these same events, with a range of 17 to 42 times greater sediment concentrations than in the reference watersheds. While high TSS tended to coincide with high flow events, differences between the reference and disturbed watersheds were still evident during baseflow periods (non-event).

Trends in TSS production over the first 4 years post-wildfire might suggest significant recovery of sediment production during that period; however, this apparent recovery trend is confounded by climate variation over the same period. Summer 2004 was generally moist, while summer 2005 was very wet, followed by two increasingly dry years in 2006 and 2007. Even during the very dry summer of 2007, sediment production remained elevated in disturbed watersheds—presumably due to the accumulation of significant channel sediment after the fire. While additional data (2008 and onward) will help to clarify these signals, significant existing stream bank failures (Figure 4) and new sediment sources suggest that the decrease in sediment production in the disturbed watersheds to concentrations similar to what has been observed in the reference watersheds will be slow.

The high-elevation Rocky Mountain headwater streams of the SRWP study area are generally oligotrophic or nutrient poor. However, during the first post-fire year, concentrations of the various forms of nitrogen (N) were 1.5 to 6.5 times higher in burned streams. Mean total N concentration was 5.3 times higher (Figure 5) compared to the reference streams the first year after the fire (Bladon et al. 2008). Nitrogen production and its relationship with stream discharge indicated very rapid recovery in the burned watersheds, with almost full recovery 3 years after the wildfire (Bladon et al. 2008). However, recovery of nitrogen production was somewhat slower in the salvage-logged watersheds, with elevated concentrations still evident 4 years after the wildfire.

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Figure 6. High post-wildfire algal production in Lynx Creek in summer of 2007 (4 years after the wildfire).

Similar to N, concentrations of all forms of phosphorus (P) were greater in the burned streams compared to the reference streams in the first post-fire year (2004) (Silins et al., in review). From 2005 to 2007, the general trend was greater concentrations of all P forms in the post-fire salvage-logged streams, followed by concentrations in the burned streams. However, unlike the pattern of post-disturbance recovery in nitrogen and other water quality parameters, return of P concentrations in the disturbed watersheds (both burned and salvage-logged) to values similar to the control watersheds has been very slow. This is likely due to the strong interactions (sorption/desorption) of P with sediments and, thus, recovery of P is likely linked to the post-fire stream sediment loading and recovery of sediment production.

Ecological Response

Elevated nutrient production after both wildfire and post-fire salvage logging has had a significant impact on stream ecology, and may have been intensified because undisturbed streams in this region are generally nutrient poor. Primary productivity (algal production) increased dramatically immediately after the fire and remains elevated in the burned and post-fire salvage-logged watersheds. Mean annual algal biomass ranged from 7.2 to 14.3 times higher and chlorophyll *a* concentration was 17.4 to 71 times higher in the burned streams compared to the reference streams (Silins et al., in review). Four years after the fire, algal biomass was still 9.8 times greater in the burned streams and 11.1 times higher in the salvage-logged streams compared to the reference streams. Differences in nutrient inputs and algal production have produced greater abundance and diversity of species in the benthic macroinvertebrate communities in both burned and salvage-logged streams compared to the reference streams. Scrapers (primarily *Ephemeroptera*) were the dominant functional feeding group in reference streams, while there was a more even distribution of predators, shredders, and scrapers in the burned streams. The increase in species diversity in disturbed streams generally reflected the influx of additional disturbance-adapted strategists or trophic generalist species.

Downstream Implications

Forested headwater areas are an important water supply source in southern Alberta, as they are in most parts of the country. Thus, while impacts to source water quality can affect a broad range of water uses, evaluating downstream impacts is often challenging because of widely differing requirements for downstream users (e.g., drinking water, stockwater, and industrial process water). However, downstream impacts of upstream disturbance can be evaluated by focusing on particular water uses. For example, operating downstream municipal drinking water utilities can become more difficult and costly after upstream disturbances from wildfire. The elevated concentrations of several water quality parameters observed in the SRWP study of burned and salvage-logged watersheds (turbidity, suspended solids, dissolved organic carbon, etc.) could potentially result in increased chemical coagulant demand, sludge production, and disinfection requirements for acceptable drinking water treatment (Emelko et al. 2009). In most cases, regardless of the specific technology use and/or the required plant size/production capacity, the treatment costs would need to increase to meet regulatory requirements. Additional public health concerns arising from wildfire-associated water quality changes include increases in microcystins (microbial toxins) and disinfection by-products, which are potentially harmful to human health. Thus, dramatic changes in source water quality can have significant cost, compliance, and public health implications for downstream municipal water use (Emelko et al. 2009)

In future research at SRWP, we plan to address numerous critical questions around what proactive measures can be taken to protect source water supplies and the treatment process performance from the deleterious impacts of disturbance. Evaluating the critical vulnerabilities within source watersheds and treatment processes will provide the opportunity for researchers to develop adaptive strategies that improve the flexibility and resiliency of drinking water treatment systems.

Providing Knowledge

To date, SRWP has provided basic information that was previously lacking on the impacts of wildfire and post-burn salvage logging on a broad range of "watershed values." These include the strong initial effects on water quality parameters, which can have ecological effects on primary and secondary producers. As expected, strongly differential patterns in early recovery have been observed among individual water quality parameters. While salvage logging did have small to moderate additional effects on water quality, the more important incremental impacts of this secondary disturbance may be related to slower rates of post-disturbance recovery because of sediment–nutrient interactions.

Forest managers require this type of information when making decisions about fire suppression priorities in critical source water regions or about post-fire management interventions such as salvage logging. Knowledge of the incremental effects of salvage logging on a range of watershed values is important in evaluating the resource trade-offs that accompany such decisions.

In the next phase of this project, the comparative effect of several harvesting strategies (including patch cutting and commercial thinning) will be studied in a paired catchment study using the two reference watersheds. The previous 5 years of study of these two watersheds for climate, discharge, and water quality parameters will form the pre-treatment calibration period for the upcoming paired basin study. Monitoring of burned and salvage-logged watersheds will continue to describe the trajectory of post-disturbance recovery of water quality parameters that have not recovered during the first phase of the research. This knowledge will continue to fill information gaps so that informed decisions may be made to improve water management practices and ensure a healthy environment in western Canada.

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Peer-reviewed Techniques Article

Comparison of Field Techniques for Measuring Snow Density at a Point

Sarah Boon, Reed Davis, Kevin Bladon, and Michael Wagner

Introduction

Field measurements form the basis of snow data from western North America, where mountainous topography often makes acquiring remote data problematic. Field data are used to determine peak snow water equivalent, assess flood hazard level, predict water supply, and ground-truth remotely acquired values of snow depth, snow density, and snow water equivalent (SWE). Measuring and understanding snow processes require methods that are known to be accurate and reliable over a range of conditions. However, few studies have evaluated the accuracy and comparability of field-based snow-sampling methods (e.g., Goodison 1978; Woo 1997). While previous studies have focused mainly on long-term, unattended installations such as snow pillows or weighing lysimeters (e.g., Lundberg and Halldin 2001), this study focused on manual point measurements of snow density.

Point snow measurements are often collected using snow tubes (e.g., Federal, Adirondack, ESC) to obtain depth, bulk density, and SWE measurements. However, detailed snow profiles can also be sampled using a combination of handheld density cutters and visual analysis to provide high-resolution data of vertical variations in snow density, crystal structure, and SWE.

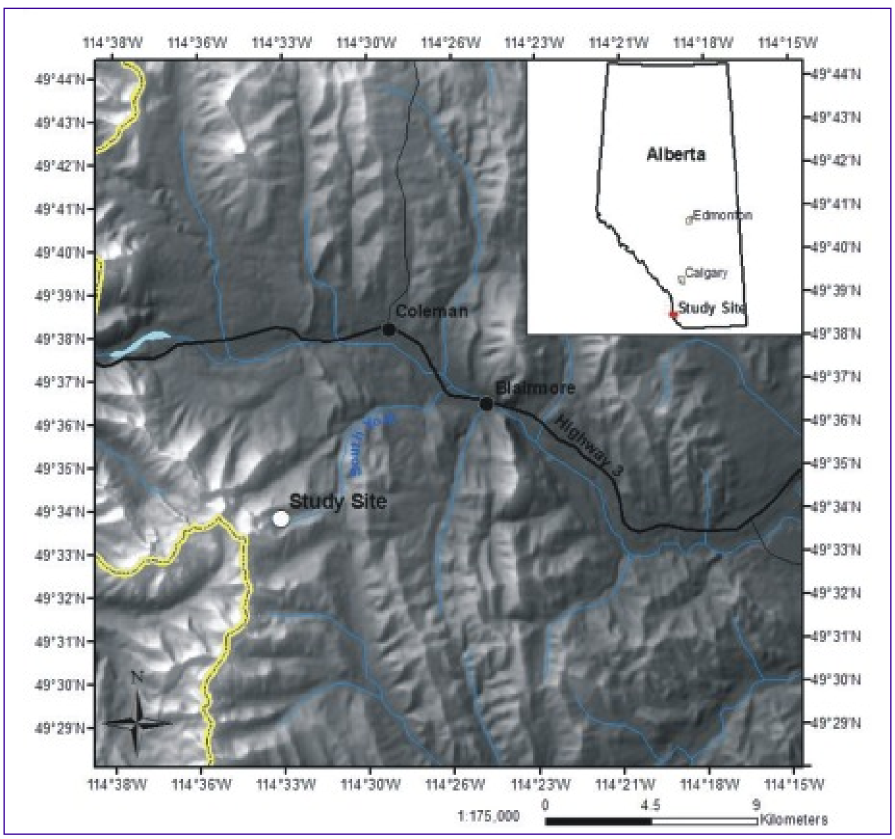

Figure 1. Study site location in the Crowsnest Pass, Alberta. The basin in which the sample sites are located is within 2 km of the British Columbia border and is delineated by the white line.

This pilot study assessed the accuracy of both handheld density cutters (Snowmetrics and SnowHydro) and snow tube (Federal) techniques by comparing each method to a control sample. Measurements from both an open and a sheltered subalpine stand were used to assess the suitability of each technique given known snowpack heterogeneity over small spatial scales (e.g., Sturm and Benson 2004). Based on these results, this article offers recommendations on the most appropriate field application of each measurement type.

Study Area

This research is part of the Southern Rockies Watershed Project (SRWP; Silins and Wagner 2007). Field sampling was conducted on February 23, 2008 in the Crowsnest Pass, Alberta (49°33.8′ N, 114°33.1′ W; 1900 m above sea level; Figure 1), in a forested area dominated by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*). Average annual snow water equivalent in these high-elevation headwater basins is approximately 400 mm. The region is typical of the Rocky Mountain alpine continental climate, with extreme temperatures and high precipitation variability due to dry/warm winter chinook winds (Barry and Chorley 1998). These winds result in freeze–thaw cycles that produce crusts, ice layers, and other crystalline changes within the snowpack (McKay and Gray 1981).

Methods

World Meteorological Organization (1994) standards were referenced when selecting sample sites, as they form the basis for international hydrometeorological data collection protocols. Snow measurements at open sites are to be collected in areas with good wind protection, and at forested sites in openings sufficiently large enough for snow to reach the ground without being affected by canopy interception. Based on these recommendations, samples were extracted from a snow pit in an open area with wind protection (Figure 2a; opening diameter > one tree height), and from a sheltered opening within the forest (Figure 2b; opening diameter < one tree height). These locations were selected to maximize forest cover differences and to reduce topographic variability by locating the sites within 50 m of one another at equivalent slope positions.

This study focused on snow density measurements which, when combined with snow depth, are used to calculate SWE. The following instruments were tested:

1. A 100-cm^3 density cutter manufactured from spot welded stainless steel by Snow-Hydro (Alaska)
2. A 250-cm^3 and a 1000-cm^3 (20 and 16 gauge, respectively) stainless steel density cutter with fully welded seams, manufactured by SnowMetrics (Colorado)
3. A standard Federal snow tube, manufactured by Carpenter Machine Works (Seattle) (Figure 3)

Weather conditions on the day of sample collection were sunny and clear, with air temperature approximately 5°C. Each pit took four field personnel an average of five hours to complete, including digging the pit, and collecting and weighing samples.

At each pit, a trench was dug from the snow surface to the ground, and a trowel was used to clean the south-facing pit face prior to sampling. This face was selected to provide maximum light to show layers and crystal structure. Flat tongue depressors served as markers between layer boundaries, providing an overall assessment of snowpack structure. A graduated 240-cm avalanche probe was placed against the snow pit face to measure layer thickness, with the zero marker at the snow-ground interface.

For the control measurement, a snow column of known volume (15 x 15 cm x snow depth cm) was collected in each pit using a rope saw (sheltered) or a knife (open). Each column was divided into smaller pieces and placed in numbered, sealed plastic bags for weighing. The accuracy of the control measurement was a function of the frequency with which the dimensions of the column top were measured. While it was difficult to maintain absolute column dimensions during cutting, which results in potentially over/underestimating density, the advantage of this method was that it incorporated all snow within a specific volume and was unaffected by edge effects or sampler size. However, given the time required and the volume of snow collected, this method is impractical in routine sampling. Comparison of sampler results with those from the control volume provided a relative measure of error.

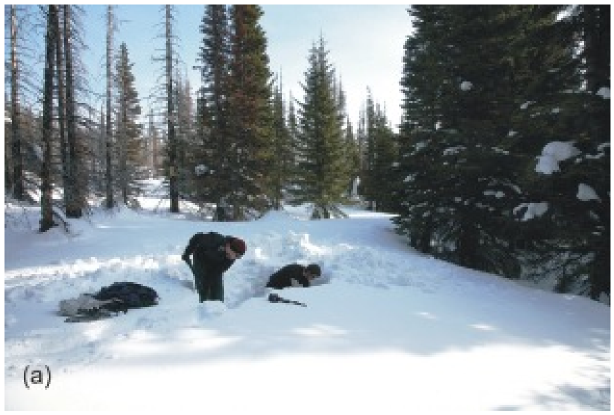

Figure 2. Open (a) and sheltered (b) pit locations.

Within each pit, snow samples were collected from the pit base to the snow surface using each density cutter, creating a vertical snow-density profile (Figure 4). The 100-cm^3 cutter was inserted with the cutting edge parallel to the snow layers. Once fully inserted, the instrument was moved gently from side to side to separate the snow sample from the snowpack. The cutter was then removed from the pack and a cutting square laid over it to extract exactly 100 cm^3 of snow. The 250- and 1000-cm^3 instruments were inserted into the pack with the cutting surface perpendicular to the snow layers. Once the cutter was fully inserted, a metal lid was inserted parallel to the top of the cutter, capturing the snow within the cutter. Each density sample was placed in a numbered, sealed bag for weighing.

Three snow cores were extracted approximately 30 cm behind each snow-pit face, using the standard Federal snow tube (BC Ministry of Environment 1981). Snow depth and height of the snow column in the tube were recorded. After removing the soil plug from the base of the core and recording its length, the sample snow core was placed into numbered, sealed plastic bags for weighing.

All samples were weighed in the field using calibrated digital scales (Ohaus 200 ± 0.1 g for density cutter samples, or 2000 ± 1 g for snow tube and control volume samples). Empty bags were weighed in the lab. The weight of each sample was calculated by subtracting the numbered bag weight from the weight of both the bag and sample. Density was calculated by dividing the sample weight by the sampler volume.

Results

The snowpack in the open pit was 205 cm deep and contained 15 layers. Ice layers were found at 10 and 40 cm above the ground surface (8 and 3 cm thick, respectively) and at the snow pit surface (1 cm thick). Depth hoar development was observed at the base of the snowpack, 5–10 cm above the

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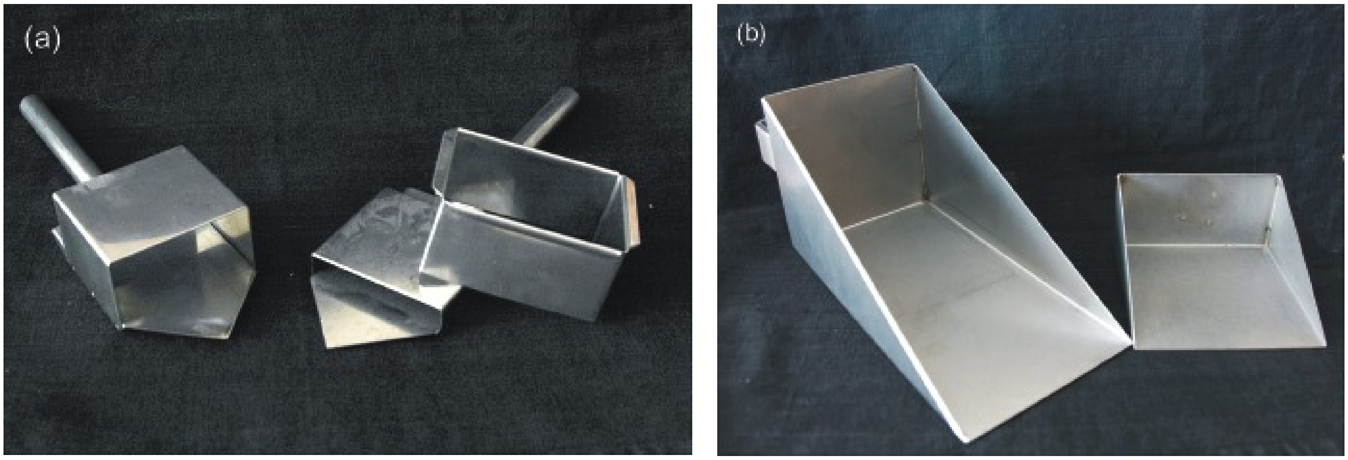
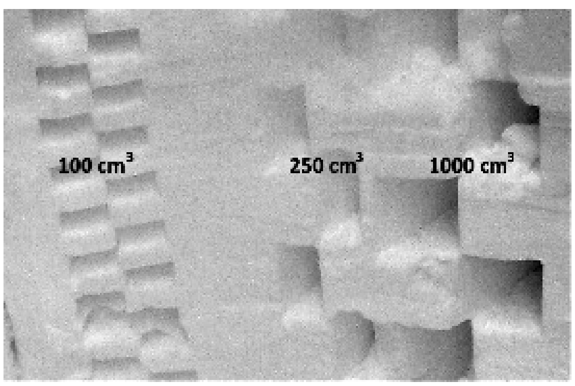


Dave Lewis

Mike Wagner

***Figure 3.** Photograph (a) shows 100- and 33-cm³ (not used in this study) density cutters; photograph (b) shows 1000- and 250-cm³ density cutters; and, photograph (c) a Federal snow tube.*

ground surface. The snowpack in the sheltered pit was 180 cm deep and contained nine layers. Ice layers 5 cm thick were observed directly at the ground surface, at 75 cm above the ground, and at the snow surface. A 5 cm thick layer of depth hoar was observed directly above the basal ice layer.



Kevin Bladon

***Figure 4.** Sampling pattern for 100-, 250-, and 1000-cm³ cutter density profiles (left to right).*

Given the dimensions of each density cutter, a greater number of samples was collected with the 100-cm³ cutter (n = 60 and 50 in the open and sheltered pits, respectively) than with the 250- and 1000-cm³ cutters (n = 20 and 19, respectively, in both pits).

Error in the control column measurement is estimated as ± 6%, based on an average 3.8 cm² deviation in the surface area of the column with depth. Average density calculated from each vertical profile was greatest in the sheltered pit (Figure 5). All measurement techniques underestimated the average density of the control column in each pit. The average density of the 250-cm³ profile was closest to that of the control column, and had the lowest relative percent error in both the open and sheltered pit (Table 1). The 100-cm³ cutter had the greatest relative percent error in the sheltered pit, and the 1000-cm³ cutter had the greatest relative percent error in the open pit.

Divergence between density profiles was observed between the 250-cm³ cutter and the 100/1000-cm³ cutters in both pits, particularly in the sheltered pit (Figure 6). In the open pit, vertical density profiles fell within a relatively narrow range, with only two samples from the 250-cm³ cutter noticeably beyond that range. In the sheltered pit, however, variability between profiles was much more pronounced and the range of density values was much greater. At several levels within the snowpack, the range in density values measured by each cutter was greater than 200 kg/m³.

Discussion

Density differences between the open and sheltered snowpack may have been driven by several factors. Canopy drip can form higher density ice layers within the snowpack, increasing snow density in sheltered locations (Kershaw 1991; Bründl et al. 1999). Snow-density variability in the sheltered pit may also have been a function of the proximity of the surrounding trees. Ice lenses sampled in one profile were not present in adjacent profiles depending on proximity to the tree crown edge; thus, the profile in which ice layers were not present had a lower average density. The resulting spatial heterogeneity in snowpack density meant that density

Table 1. Relative percent error in the density measurement of each snow sampler versus the control column

Instrument	Open (%)	Sheltered (%)
100 cm³	–7.6	–17.2
250 cm³	–4.3	–4.8
1000 cm³	–9.9	–11.1
Snow tube	–5.9	–11.8

profiles sampled in each pit did not represent identical conditions. However, comparisons can be drawn between samplers at locations where similar crystal structure is observed between profiles. Field observations of sampler performance within each profile can also be used to determine the utility of each under varying pit conditions. Spatial snowpack heterogeneity, in combination with errors in control column collection, also increases the difficulty in assessing absolute differences in sampler accuracy. However, relative differences can be addressed.

The 100-cm^3 cutter had difficulty sampling ice layers given its small size and thin metal construction, thus underestimating snow density in the sheltered snowpack. The larger samplers, however, had no trouble sampling ice layers. In some cases, density samples contained air pockets where snow broke off during the extraction process—depth hoar in particular lacked cohesion to fill the cutters. Samples with air pockets were resampled immediately, as loss of snow from a sample would underestimate snowpack density.

The density cutters were difficult to manoeuvre at the base of the snow pit as the cutting edge caught either on the ground surface or on the basal ice layer. Snow also adhered to the cutters as a result of sunlight or warm hands, melting and refreezing to the steel and potentially decreasing density measurements. Additionally, the lid of the 250- and 1000-cm^3 cutters was in some cases difficult to insert flush with the cutter, thus samples may have contained more than the defined volume. Outliers in the open and sheltered density profiles (Figure 6) may therefore be the result of air pockets (density underestimated) or oversampling (density overestimated).

While some of these errors can be minimized by following careful field procedures, under- and over-sampling problems are more difficult to avoid. Additionally, if a less accurate density cutter is used (e.g., 1000 cm^3), a larger sample set must be collected to overcome the effect of measurement error (Winkler and Spittlehouse 1995), thereby increasing the sampling time required.

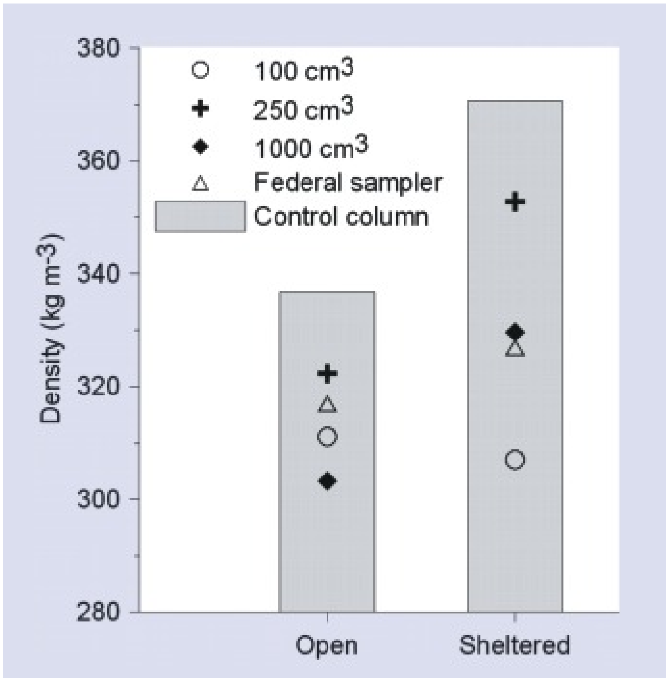


Figure 5. Average snow-pit density from each measurement technique.

Previous studies have found that the Federal snow tube has an approximate 10% error (Farnes et al. 1982). Comparison of the open and sheltered snow tube samples with the control columns gives 5.9% and 11.8% error, respectively. The open pit was thus within the previously reported error bounds, while the sheltered pit slightly exceeded it. While snow tubes often have greater percent error in shallow snow cover (Work et al. 1965), in deep snowpacks, such as those at the SRWP study site, the Federal snow tube continues to be an appropriate method for measuring snow density.

Conclusion

The 250-cm^3 cutter is best suited for measuring density profiles in deep snowpacks, as it captures some variation between snow layers while also maintaining the lowest relative percent error versus the control volume in both pits, and can also cut through ice layers. Unfortunately, the 100-cm^3 cutter cannot sample ice layers, and requires three times the number of samples when compared with the 250- or 1000-cm^3 cutters. This makes it more useful in shallow, ice-free snowpacks. The 1000-cm^3 cutter requires the greatest care to prevent oversampling, but could be most useful for incorporating high snowpack heterogeneity into a larger volume sample. Since the vertical dimensions of the 250- and 1000-cm^3 cutters are identical, the same time will be required to collect a complete sample set. Relative to the snow tube, cutters are smaller, lighter, and less cumbersome to transport, but require more time and energy to collect measurements and cannot efficiently collect spatially distributed samples. While increasing the number of snow-pit profiles examined with cutters would be expected to reduce the error, the time requirements for this type of sampling effort are most likely to be prohibitive. For a 2-m snowpack, a snow tube sample requires 2 to 5 minutes per sample site, while the density cutters require upwards of 45 minutes. The snow tube is the preferred method for extracting average density, or measuring spatial variability in SWE, as error in individual measurements can be averaged over a larger number of measurements. It is also most useful when a large number of samples are required (e.g., when estimating differences between stand types or treatments). In situations where a detailed density profile is desired, however, the density cutters are recommended.

It is important to note that the specific data requirements of each snow sampling study will determine which point snow measurement technique is selected. For spatially distributed estimates of maximum SWE required for flood forecasting or water availability, the snow tube is most appropriate given the speed and accuracy of sampling over large areas. For process-

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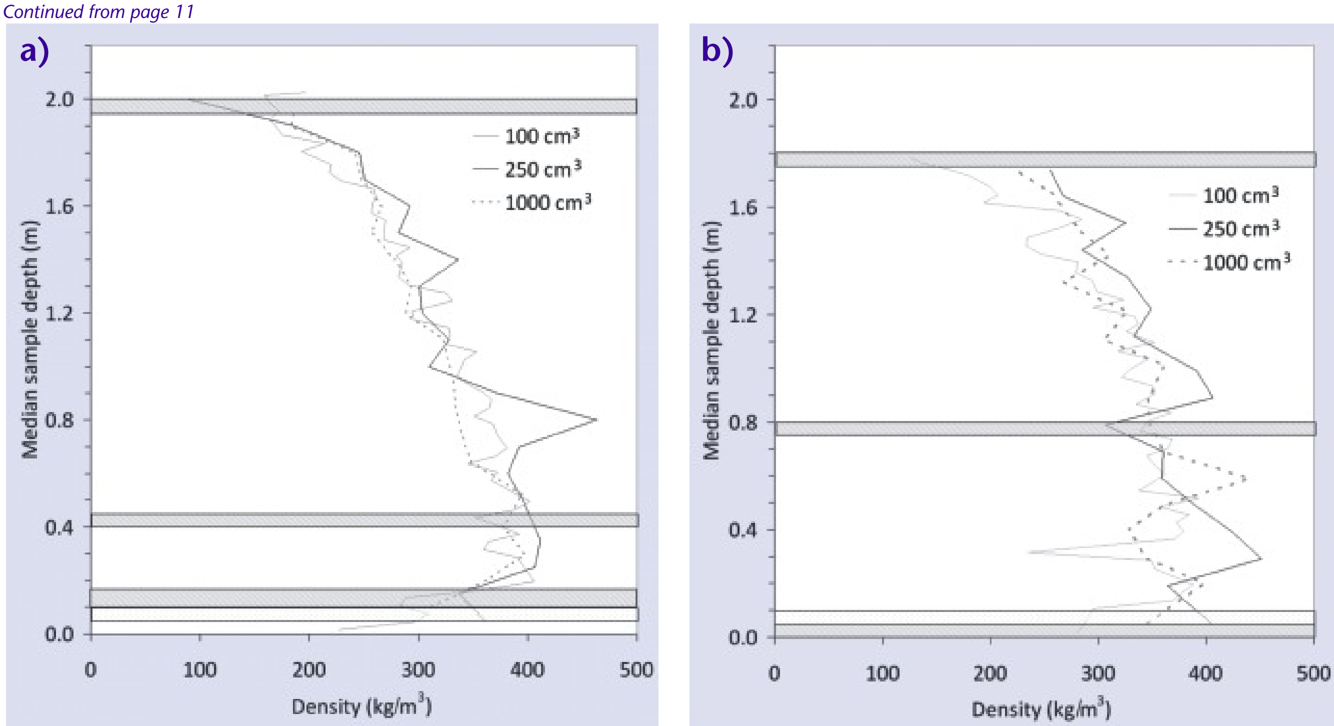

Figure 6. Vertical density profile in the open (a) and sheltered (b) snow pits. Zero cm is the snow-ground interface. The shaded bar indicates an ice layer and the white bar indicates depth hoar layer.

based studies, detailed information on density profiles is often desirable to assess snowpack processes and to validate output from remote sensing platforms that can be affected by internal snowpack stratigraphy. In these situations, the 250-cm^3 cutter is recommended due to its low relative error, and its ease of use in deep snowpacks with internal ice layers. The 100-cm^3 cutter has slightly lower relative error than the 250-cm^3, and can be effective in shallow snowpacks without ice layers, where the greater time investment for sample collection and the inability to sample ice layers are less of a problem. The 1000-cm^3 cutter is difficult to manoeuvre and most likely to oversample, but could be useful when sampling a deep, snowpack where larger sample volumes are required to overcome snowpack heterogeneity.

This research is being expanded to assess the utility of each measurement technique at different times of year and with varying elevation, aspect, and vegetation cover, and to assess the accuracy of various methods of control column sampling. This will help identify the optimal measurement technique to apply over a range of real-world conditions.

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Information Note

British Columbia Terrain, Soil, and Ecosystem Mapping Databases Now Available Online

Deepa Filatow and Maija Finvers

Introduction

Do you ever need to know the location or extent of sensitive soils? Of riparian or wetland zones? Of areas of potential slope instability? Or of areas of very thin materials over rock? What about finding where there are potential erodible soils as sources of stream sediments? Or potential sources of aggregates for road building? Or potential habitat for burrowing species?

Terrain and Ecosystem Mapping inventories can be used to answer these questions. Other information that may be derived from terrain and terrestrial ecosystem data include:

- Erosion potential
- Dominant surficial materials
- Slope stability
- Areas of thick or very thin surficial materials
- Ecosystem/material presence
- Sensitive ecosystems
- Structural stage
- Ecological condition
- Wildlife habitat
- Dominant ecosystems

This article provides an introduction to the datasets available and discusses how to access this data.

Description of Mapping Project Types

Terrain Mapping (TER) provides information on the classification and distribution of surficial materials (the unconsolidated sediments on top of bedrock), landforms (the surface expression or three-dimensional shape of surficial materials), and geomorphological processes (the mechanisms that continue to deposit and modify surficial materials). Terrain mapping is completed using air photo (or digital earth image) interpretation, usually with field checking. There are three common types of terrain maps: terrain inventory, terrain stability, and bioterrain. Each contains basic terrain information, while the latter two contain additional attributes and focus on slope stability and ecology respectively. Figure 1 shows the extent of terrain data (in GIS format) available from the BC Ministry of Environment (MOE) by request to *soilterrain@victoria1.gov.bc.ca* or via self-serve data discovery and download from the Land and Resource Data Warehouse (LRDW). (See Table 2 next page for websites and contact information for all datasets discussed.)

Soil mapping provides information on the classification and distribution of soil types. It shows the spatial distribution of soil associations—groupings of soils with the same parent material, climate, and dominant vegetation that occur as repeated patterns in the landscape. Soil is the naturally occurring, unconsolidated mineral or organic materials at the surface of the earth which is capable of supporting plant growth. Unique soil types form as a result of surficial material, biota, climate, topography, and time. As with terrain mapping, soil mapping is based on air photo (or digital earth image) interpretation with field checking. Figure 2 shows the extent of the

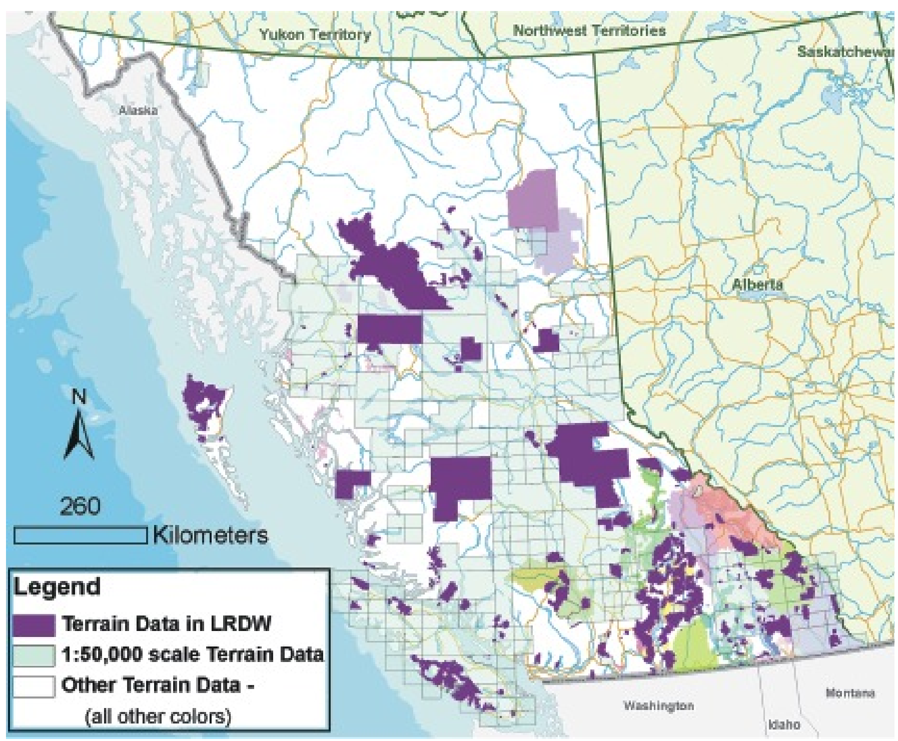

Figure 1. Terrain mapping data available from MOE.

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Table 1. Types of ecosystem and terrain inventories

Type of inventory	Features mapped and classified	Inventory method and field data availability	Typical scale range	Data currency	Primary drivers for data collection and primary uses
Terrain inventory mapping	Terrain = surficial material, landform, and process.	Air photo interpretation and field survey. Field data may be archived.	1:50 K–250 K	1950– 1980	General purpose inventory for landscape planning. Background information for more detailed studies.
Terrain stability mapping	Terrain, as above, and: drainage, slope, stability class. *erosion potential *potential for sediment delivery to streams (from surface erosion and/or landslides)	Air photo interpretation and field survey. Field data may be included as scanned field cards in report appendices, with regional offices, in archives, or with the mapper.	1:10 K–50 K	1980–present	**Reconnaissance mapping:** Landscape-level planning to identify areas requiring more detailed study, flagging areas that warrant on site investigation by a terrain stability expert. **Detailed mapping:** Planning, terrain hazard and constraint identification, other related interpretations. Detailed terrain description can be used to derive other information, e.g., aggregate resources, potential for surface or landslide induced sedimentation to streams.
Bioterrain mapping	Terrain as above, with ecological focus, and drainage (also delineates other influences on ecology such as aspect).	Air photo interpretation and field survey. Field data captured using Venus.	–	1980–present	Used as an input to PEM and TEM.
Terrestrial ecosystem mapping	Terrestrial ecosystems = ecosystem unit, site modifier, structural stage,and bioterrain.	Air photo interpretation and field survey. Field data captured using Venus.	1:10 K–50 K	1980–present	Interdisciplinary tool for a multitude of resource land management applications. Used for operational and regional planning.
Predictive ecosystem mapping	Terrestrial ecosystems, as above.	Modelling using multiple datasets. Field data captured using Venus.	1:20 K–50 K	1990–present	Interdisciplinary tool for a multitude of resource land management applications. Used for regional and strategic landscape-level planning.
Sensitive ecosystem inventory	Rare and fragile terrestrial ecosystems.	Air photo interpretation and field survey. May or may not be based on TEM.	1:20 K	1990–present	Municipal and regional district planning.
Soil mapping	Soil types: Soil associations—soils with the similar age, parent materials, climate, and dominant vegetation.	Air photo interpretation and field survey. Soil sample data stored in BCSIS.	–	1930–early 1990s	Landscape planning, basis for agricultural and forest soil capability and a variety of suitability mapping, soil drainage, surficial material mapping, and basis of early versions of ecosystem mapping.

Table 2. Sources of information and contacts

Index maps and metadata in the LRDW are available via:
Ecosystem and Terrain Mapping Data Inventory http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=53599&recordSet=ISO19115
Ecosystem and Terrain Mapping Project Boundary Index http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=51798&recordSet=ISO19115
Terrain Mapping Project Boundary Index http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=53579&recordSet=ISO19115
Terrestrial Ecosystem Mapping Project Boundary Index http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=53539&recordSet=ISO19115
Predictive Ecosystem Mapping Project Boundary Index http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=53519&recordSet=ISO19115
Sensitive Ecosystems Inventory Project Boundary Index http://aardvark.gov.bc.ca/apps/metastar/metadataDetail.do?recordUID=53559&recordSet=ISO19115
Terrain data:
For the MOE Terrain home page: http://www.env.gov.bc.ca/terrain
For information on the types of terrain mapping http://www.env.gov.bc.ca/terrain/terrain_files/types.html#terrainstability http://www.degifs.com/pdf/TS%20Mapping%20User%20Guide.pdf
For information on terrain classification standards http://www.env.gov.bc.ca/terrain/terrain_files/standards.html#terrainstds
A user guide for Terrain Stability Mapping http://www.degifs.com/pdf/TS%20Mapping%20User%20Guide.pdf
For access to GIS and scanned map files and other sources of terrain data http://www.env.gov.bc.ca/terrain/terrain_files/access.html
Soil data:
For access to 1:50 000 scale GIS data (.gdb or shape/dbf formats) ftp://fshftp.env.gov.bc.ca/pub/outgoing/Soil_50K_FGDB/
For access to soil sample site, profile, and lab analysis data (BCSIS) ftp://fshftp.env.gov.bc.ca/pub/outgoing/Soil_Data/BCSIS/
For the MOE Soils home page, and access to scanned map files and other sources of soils data http://www.env.gov.bc.ca/soils/
For more information on soils classification standards visit http://www.env.gov.bc.ca/terrain/terrain_files/standards.html#soilstds
Terrestrial ecosystem mapping, predictive ecosystem mapping and sensitive ecosystem inventory data:
Terrestrial Ecosystem Mapping (TEM), Predictive Ecosystem Mapping (PEM), and Sensitive Ecosystem Mapping (SEI) and information on how to access data (on Ecology home page) http://www.env.gov.bc.ca/ecology/
For TEM, PEM, SEI reports and data, including VENUS data, on EcoCat http://www.env.gov.bc.ca/ecocat/
Other BC data:
For Data Discovery, Data Distribution Service via the Land and Resource Data Warehouse (LRDW) http://aardvark.gov.bc.ca/apps/metastar/home.do
For other BC Datasets, including web-based interactive mapping–GeoBC http://www.geobc.gov.bc.ca/
For further information, please contact the authors, via email: soilterrain@victoria1.gov.bc.ca

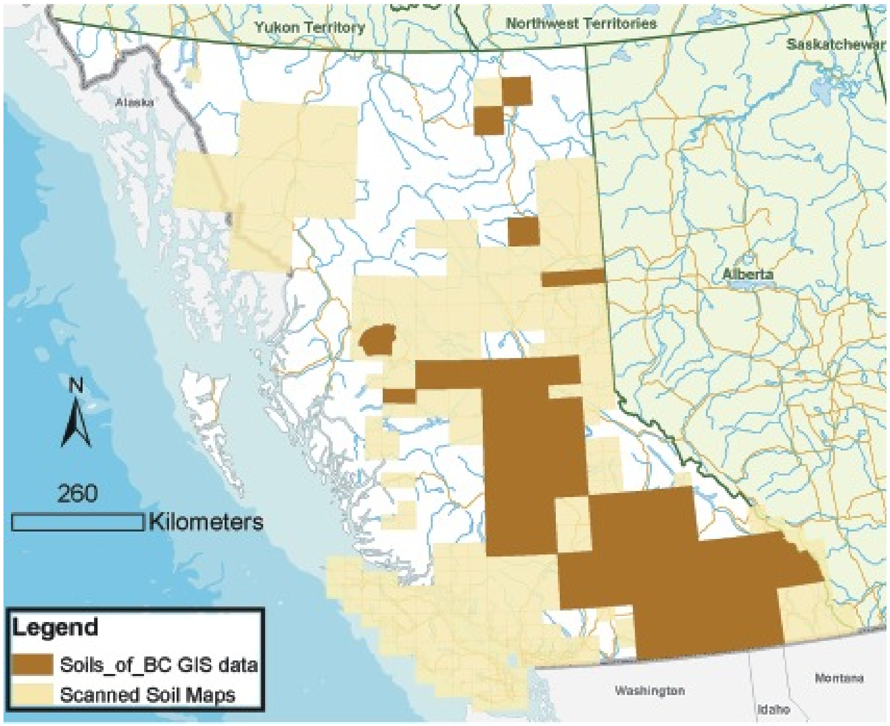

Figure 2. Soil mapping data available from MOE.

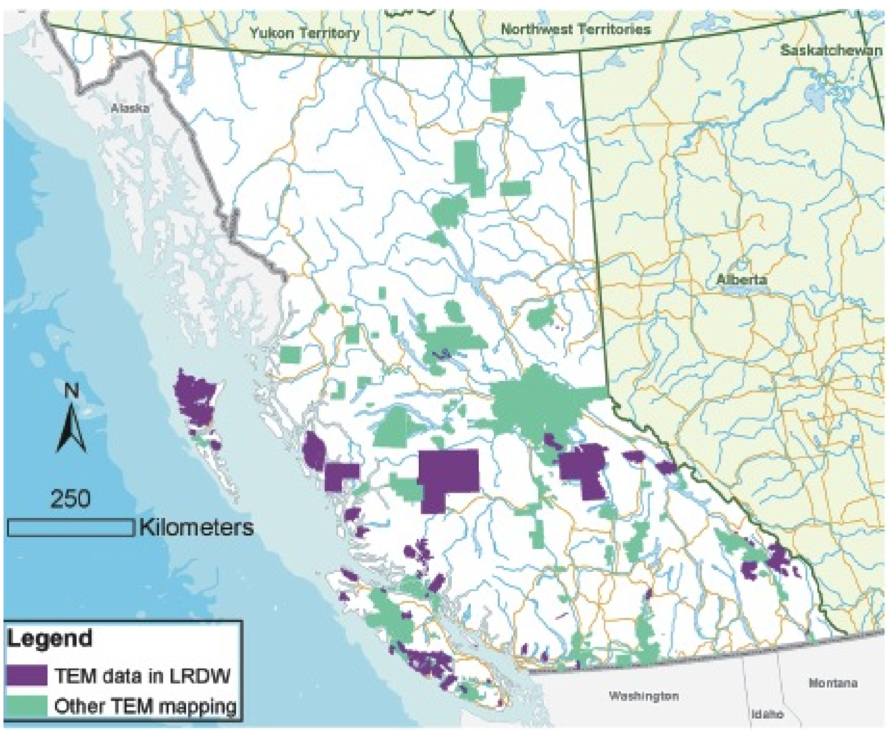

Figure 3. Terrestrial Ecosystem Mapping (TEM) available from MOE.

1:50 000 soil Geographic Information Systems (GIS) data available from the MOE. Soil sample site, soil profile, and soil lab analyses data are also available from the BC Soil Information System BCSIS database.

Ecosystem Mapping provides information on the classification and distribution of ecosystem units (including site series, site modifiers, and structural stages). There are two basic types of ecosystem mapping: Terrestrial Ecosystem Mapping (TEM) and Predictive Ecosystem Mapping (PEM). Both approaches stratify the landscape into map units according to a combination of ecological factors (primarily climate, physiography, surficial material, bedrock geology, soil, and vegetation); however, there are some differences. TEM uses manual air photo interpretation supported by extensive field sampling to classify and map ecosystems. PEM uses existing information and knowledge to model ecosystems across the landscape. Figures 3 and 4 show the extent of TEM and PEM data currently available from the MOE via EcoCat or self-serve data discovery and download from the LRDW. Associated ecosystem field sampling data is also available from MOE via EcoCat.

The Data

The majority of the terrain, soils, and ecosystem mapping projects were conducted over the past 30 years, and MOE and precursor agencies acquired the data from multiple sources (e.g. industry, consulting firms, government, and non-government agencies). Mapping data continues to be collected through government-funded inventories (such as the Forest Investment Account), to meet government requirements (such as Environmental Assessment Office submissions) and through partnerships (such as those with municipal, regional, and federal governments and non-government organizations). Table 1 provides a summary of project types, methods of data acquisition, typical map scales, data vintage, and the primary drivers for the mapping projects or uses of the data.

Data Management

The custodianship of terrain, terrain stability, landslide inventory, soil and ecosystem mapping, as well as terrain, soils, and ecosystem field data (including site, soil profile, terrain, vegetation, wildlife, and soil lab analysis data) is currently the responsibility of two subject area experts and two information specialists in the Ecosystem

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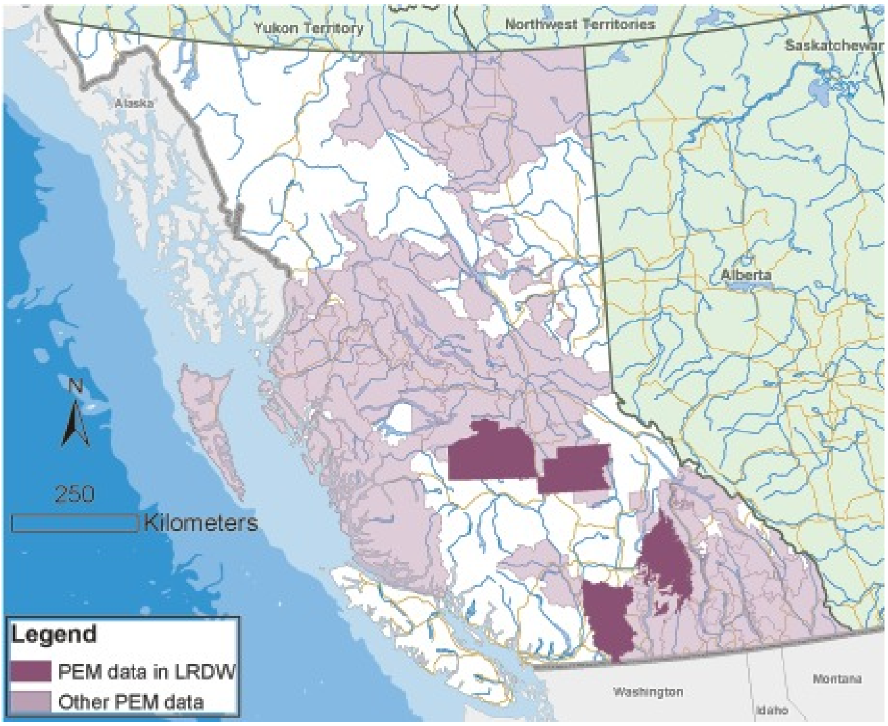

Figure 4. Predictive Ecosystem Mapping (PEM) available from MOE.

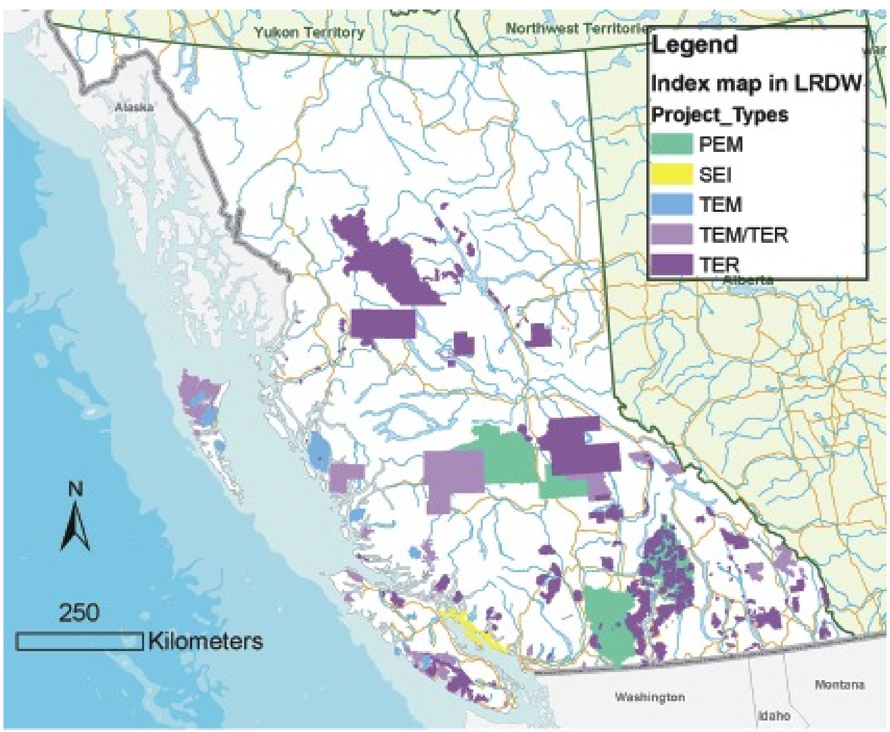

Figure 5. Index map currently available in the LRDW.

Branch of the MOE. Their goal is to improve data quality, access, and use of these datasets.

In September 2008, the Soil, Terrain, and Ecosystem Mapping Project Boundary Index was published to the LRDW—the provincial data repository managed by GeoBC. This layer shows project boundaries and attributes for terrestrial ecosystem, predictive ecosystem, sensitive ecosystems inventory, and terrain mapping projects (see Figure 5). Soil data will be added soon.

This online index map (to be made available via iMap) will help users identify where information is available, whether it may serve their needs, and how to access the project datasets. Additional data types (e.g., soils) and project boundaries will be added to the index as more data is standardized/converted. Ongoing standardization/conversion of the detailed data (polygons, points, attribute tables, and lines) and the development of the associated databases for housing these data will facilitate its publication to the LRDW.

All of these initiatives aim to improve access to the terrain, ecosystems, and soils data, and to improve the utility of this data for a wide variety of purposes and users.

Efforts are also underway to publish a similar index map showing the distribution of scanned maps (legacy soils terrain and other theme maps) that were previously either unavailable or available only through print-on-demand services. These scanned map files are available upon request to the MOE (see Table 2).

All of these initiatives aim to improve access to the terrain, ecosystems, and soils data, and to improve the utility of this data for a wide variety of purposes and users.

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Peer-reviewed Synthesis Article

Forest Management Effects on Groundwater: Large Knowledge Gaps Persist

by Brian Smerdon, Todd Redding, and Jos Beckers

Groundwater is an integral part of the hydrologic cycle, contributing to streamflow from headwater hillslopes (Moore and Wondzell 2005), to base flow to streams in the low flow season (Pike and Scherer 2003), and to maintaining ecosystems (Brown et al. 2007). Groundwater is also the drinking water source for 25% of British Columbians, and there is a growing need for greater knowledge about the effects of forest management on groundwater (Pike and Scherer 2003; Redding and Nickurak 2008; Redding et al. 2008).

Currently, very little is known about the interactions between forest management activities (e.g., harvest practices and road building) and groundwater resources. This is, perhaps, partly because groundwater inventory and assessment has typically been limited to populated areas of the province, and, again perhaps, partly because the role of groundwater within a forested watershed has typically been overlooked in forest management.

This article provides an overview of the available literature on the potential implications of forest management activities (e.g., harvest operations, road building, revegetation, and mountain pine beetle infestation) and on aspects of groundwater hydrology (e.g., water table position, low flows, and groundwater recharge). This overview summarizes a more in-depth synthesis publication (Smerdon et al. 2009), and builds on recent summaries of groundwater hydrology (Smerdon and Redding 2007) and groundwater management issues (Douglas 2008). Generally, there are very few published case studies on the direct impact of forest management activity on groundwater (e.g., impact to aquifers), so we conclude this overview by outlining a classification of broad-scale hydrogeologic regions for British Columbia to provide a conceptual framework for evaluating potential future forest management effects. The intent of these unique regions is to create further discussion on the role of groundwater in forested watersheds and to provide a framework to translate and/or transfer the findings of published studies from other regions.

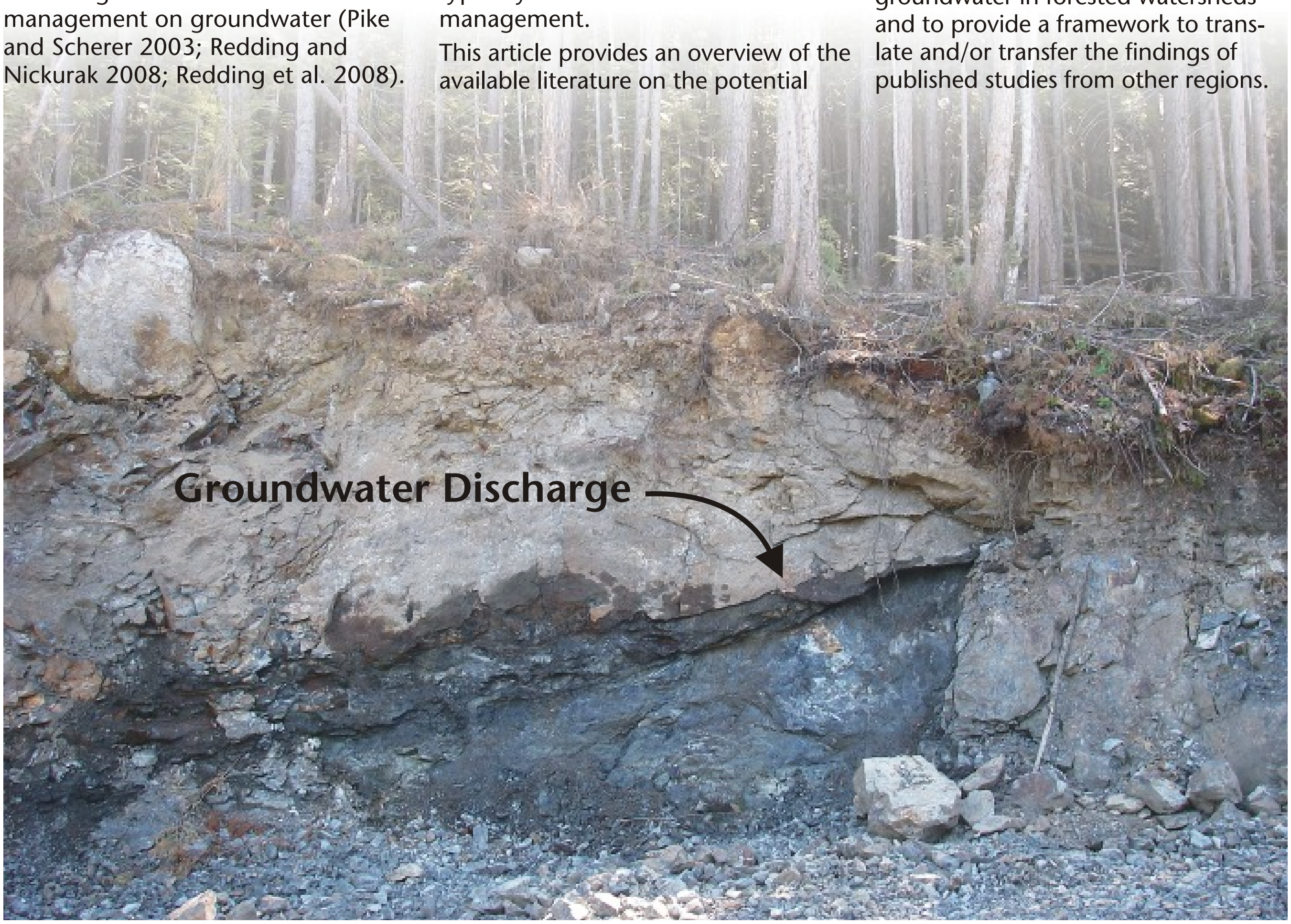

Figure 1. Groundwater flowing through bedrock fractures intercepted by a road cut, Kootenays, BC.

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An Overview of Published Studies

There are many published studies on the effects of forest management on surface hydrological processes, and comprehensive reviews have been written by Moore and Wondzell (2005), Pike and Scherer (2003), and Bonell (1993). However, very few studies have focused on the direct link between forest management activities (both harvesting and road construction) and groundwater (i.e., subsurface water in the saturated zone). Of the few studies available in scientific literature, some have reported on the effects of timber harvesting (the removal of trees through clear, partial, or selective cutting) and the observed changes to the position of the water table, the estimated changes to catchment water yield, and the changes to stream base flow. A summary of published studies that specifically focus on groundwater hydrology has been divided into (1) effects of harvest on water table position (Table 1) and (2) groundwater recharge (Table 2). Only a few studies have reported on the effects of road construction and silviculture activities.

Effect of Harvest on The Water Table

Forest harvesting generally leads to a rise in the water table elevation towards the ground surface, primarily due to a reduction in interception and evapotranspiration provided by forests. The effect of changes in canopy rain/snow interception has been relatively well documented; however, changes in plant transpiration before and after harvest are complex and depend on the vegetation type. The net effect is that wetter soil more readily conducts water to the saturated zone, which in turn may increase the elevation of the water table (see Table 1).

The degree of water table rise will depend on specific watershed characteristics, including bedrock geology, surficial geology, soil type, and landform topography. At Carnation Creek on west Vancouver Island, late summer water-level rises of 30 to 50 cm on the floodplain persisted for 10 years post-harvest (Hetherington, 1998), and contributed to the well-documented process of triggering preferential flow in humid, steep watersheds (e.g., Beckers and Alila 2004). For the Vanderhoof Forest District, Rex and Dubé (2006) have noted elevated water table levels in lowland areas (e.g., toe slopes, wetlands, or lowland landscapes) after harvesting (Table 1). For lower relief watersheds with a drier climate on the Boreal Plains, a water table increase was found to be 26 cm following harvest (Evans et al. 2000).

In each of these environments, an increase in water table elevation may have differing effects on forest management operations (e.g., trafficability) depending on the slope of the terrain and soil characteristics. Wetter ground is promoted when

TABLE 1. Overview of published studies: Effect of harvest on water table

Source	Study site	Location	P (mm)	Forest management practice and change to water table	
Hetherington (1998)	Carnation Creek	Vancouver Island, British Columbia	2100–4800	CC	30- to 50-cm rise that persisted for 10 years following harvest.
Fannin et al. (2000)	Carnation Creek	Vancouver Island, British Columbia	2100–4800	CC	50- to 150-cm rise (approx.) following individual storm events. Large spatial variability due to soil conditions, but all water table response was rapid. An upper limit to pressure head increase was observed, above which preferential flow pathways activated.
Rex and Dube (2006)	Vanderhoof Forest District	central British Columbia	496	CC + MPB	10 cm (approx.) higher water table in toe-slope of cut area compared to MPB-kill area. 30 cm (approx.) higher water table in upland of cut area compared to MPB-kill area.
Evans et al. (2000)	TROLS	Lac La Biche, Alberta	468	PC	26 cm higher in cut area, compared to uncut area.
Dube et al. (1995)	Beaurivage Forest	St. Lawrence lowlands, Quebec	957	CC	7- to 52-cm rise, depending on soil texture.
Pothier et al. (2003)	Villroy	St. Lawrence lowlands, Quebec	510	PC + CC	Up to 22-cm rise in cut areas. Water table rise increased linearly with percentage of cut area in the first year following harvest. Five years after harvest, water tables remained elevated, but were less dependent on the percentage of area cut.
Megahan (1983)	Pine Creek	central Idaho	890	CC	90-cm rise in water table, decreasing to approximately 40-cm after 2 years.
Bliss and Comerford (2002)	-	Gainesville, Florida	1150	CC	21- to 49-cm rise after 900 days. Larger seasonal fluctuations observed for 4 years following harvest.
Peck and Williamson (1987)	Collie River Basin	western Australia	820–1120	CC + PC	100- to 400-cm rise following wet season. Water table increased by 260-cm/yr in clearcut areas and 90-cm/yr in partially cleared areas.

CC – clearcut PC – partially cut MPB – mountain pine beetle surface water drainage density and understorey vegetation are decreased, and the area of poorly drained soils and pine cover are increased (Dubé and Rex 2008). In the Vanderhoof Forest District, summer logging due to wet ground has been stopped in favour of logging when the ground is frozen and generally more stable (Rex and Dubé 2006). In steep mountainous watersheds, a rise in the water table may lead to a greater risk of slope failure (Sidle and Ochiai 2006). For each of these scenarios, additional constraints are imposed on logging operations, illustrating the potential feedback between forest harvest and trafficability.

A rise in the water table and wetter ground can also affect the selection of appropriate silvicultural systems (Pothier et al. 2003) and post-harvest species selection. Forest regeneration may be affected by higher water tables because some tree species do not tolerate saturated conditions in the rooting zone; this may decrease productivity or result in regeneration failure (e.g., Landhausser et al. 2003). However, vegetative species that promote higher evapotranspiration may aid water table decrease following harvest. These "nurse crops" would contribute to site water-balance recovery in recently harvested and replanted sites (Landhausser et al. 2004). Reclamation of a vegetative cover that has similar evapotranspiration characteristics as the original species is an important step toward minimizing long-term effects of harvesting on groundwater systems and maintaining forest productivity.

Effect of Harvest on Groundwater Recharge

Groundwater recharge (water entering the groundwater flow system) is a difficult component of the water cycle to quantify (de Vries and Simmers 2002), but may be inferred from changes in water table position, watershed yield, and base flow (in some cases). The rate of groundwater recharge and corresponding discharge, in the form of base flow, is critical for maintaining aquatic habitats. In cold climates, where many surface streams and lakes freeze in the winter, groundwater inflows or seepage can maintain open water, thus providing temperature refuge for fish (Power et al. 1999). The winter inflows also help maintain an optimum environment for the overwintering of sockeye salmon eggs (Leman 1993), and provide free-flowing water for migration (Douglas 2008). In summer, groundwater inflows to streams may provide a buffer for stream temperatures (e.g., Story et al. 2003) and dampen diurnal temperature fluctuations, which are critical for fish survival (Douglas 2008).

Similar to the rise in water table that can be expected following harvest, the effect of wetter soil conditions may also increase groundwater recharge rates. Watersheds in steep terrain would not be expected to have an appreciable amount of groundwater recharge compared to runoff (e.g., Hudson and Anderson 2006). Although there are no published studies that directly measured increased rates of groundwater recharge following harvest, there are a few that indicate increases in watershed yield, which may be a result of higher groundwater recharge. For example, in the northeastern US, for a few years following harvest, a harvested headwater watershed was found to supply more base flow that didn't appear to be generated from shallow storm flow (Bates 2000). In another case, recharge increased by 68 mm/year for 6 years following harvest (Bent 2001). Similar results are summarized for snowmelt-dominated hydrologic regimes by Pike and Scherer (2003). At the Upper Penticton Creek Experimental Watershed in the Okanagan Basin, the results of stand water-balance models show increased drainage of water from the soil rooting zone following harvest and disturbance (e.g., mountain pine beetle) as compared with undisturbed mature forest stands (Spittlehouse 2007).

The implications of such changes in recharge will vary according to watershed characteristics (e.g., bedrock geology, surficial geology, soil type, and topography), and further study of the relationship between groundwater recharge and streamflow in forest management areas is needed to

TABLE 2. Overview of published studies: Effect of harvest on groundwater recharge

Source	Study site	Location	P (mm)	Management practice and inferred change in groundwater recharge	
Bates (2000)	Fernow Experimental Forest	West Virginia	1470	PC	Harvested watersheds supply more low flow (base flow) to headwater streams, due to higher soil moisture in the years following harvest. Minor amount of (event) storm noticed, compared to deeper subsurface flow.
Bent (2001)	Cadwell Creek	Massachusetts	1174	PC	Groundwater recharge increased by 68 mm/yr for 6 seasons following harvest.
Cornish (1993)	Karuah	Australia	1450–1750	PC	Yield increased 150 to 250 mm/yr following harvest, depending on percentage of area cut. Increased recharge and overall water yield remained higher for 3 years following harvest.
Bren (1997)	Cropper Creek	southeast Australia	660	CC	Increase in amplitude of diurnal fluctuation in streamflow following removal of slope vegetation due to increased subsurface flow.
Cook et al. (1989)	Western Murray Basin	South Australia	340	CC	Recharge found to increase by 20 mm/yr very gradually following harvest (~200 yrs based on simulation modelling)

CC – clearcut PC – partially cut

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Continued from page 19

quantify the hydrologic mechanisms that control flow regimes. The magnitude of increase in water yield, and potentially the increase in groundwater recharge, may be linearly related to the percentage of area cut (partial harvesting or clearcutting), especially in the first few years following harvest (e.g., Stednick 1996). Groundwater flow systems will adjust to the increased water input, and this effect may be short- or long-lived, depending on the scale of the flow system. Recharge that is part of a local scale system may discharge relatively quickly to nearby headwaters (e.g., Bren 1997), such that effects of harvesting could be detectable and/or ecologically significant. On the other hand, the effects of relatively short-term forest disturbances (i.e., decades) may not necessarily be detectable in larger-scale flow regimes (e.g., regional-scale flow systems) that tend to respond over long time scales.

Forestry Roads and Groundwater Hydrology

Development of forestry roads has been shown to have an effect on surface drainage networks, while the only effect of road construction on groundwater has been documented for steep, mountain settings (e.g., Wemple et al. 1996). Roads that cut into a hillside may intersect shallow groundwater, creating a seepage face along the road cut (Megahan and Clayton 1983), and redirect flow as surface water in ditches. Depending on how the road network connects with the natural stream network (i.e., culvert discharge locations), this may influence the timing and magnitude of peak flows as moving water could reach the stream more rapidly than subsurface water. Forestry roads that intercept shallow groundwater may also reduce groundwater flow to downslope environments (e.g., springs and seepage areas). At Carnation Creek on Vancouver Island, road construction at different locations was found to either increase, decrease, or result in no change to downslope water table elevations (Hetherington 1998). The differences in downslope effects at Carnation Creek were related to the location of the road and construction practices. The combined effect may have a significant impact on aquatic ecosystems that rely on specific rates and timing of groundwater discharge or duration of base flow.

In more gently sloped terrain, the potential for road cuts to intersect groundwater flow systems is typically lower than in steep terrain, except near groundwater discharge areas (streams, wetlands) where the water table is shallow. Under such conditions, the different physical attributes of the road compared to the surrounding landscape may become more important, with the compacted road surface having the ability to limit infiltration. Whether this effect is significant depends on the area of a watershed covered with compacted surfaces (Putz et al. 2003), as well as the location of roads and the type and quality of road construction.

Regional Groundwater Resources

Regional-scale groundwater flow systems tend to buffer short-term variability in climate and land-use changes (including forest management activities), but integrate long-term changes, making deleterious impacts more difficult to reverse. With forest harvesting, this means that widespread changes in upland recharge areas could go unnoticed for decades in adjacent valley bottom aquifers. The effects may also be masked or magnified by climate variation and change. Widespread forest clearing in western Australia throughout the 1950s and 1960s has provided a good example of the timing involved for changes to propagate through groundwater regimes. Low rainfall areas (850 mm/yr) and high rainfall areas (1120 mm/yr) were clear-cut, and groundwater response was observed over the following decades (Hookey 1987). For the flow systems in western Australia, water budget studies and simulation modelling have shown that groundwater for the basin re-equilibrates 25 to 30 years after cutting.

To date, no studies have been conducted in British Columbia to investigate potential large-scale effects of harvest on regional groundwater resources. Studies that focus on the dynamics of complete groundwater flow systems and mechanisms that govern groundwater recharge and discharge in forest management areas are therefore warranted, particularly in the context of the current large-scale mountain pine beetle infestation and associated salvage harvesting in central British Columbia. Rex and Dubé (2006) have found that low-relief watersheds with fine-textured soils and dead pine stands have wet soils and a raised water table. These preliminary findings suggest that cutblocks may have higher water table elevation than beetle-kill areas, and the difference between beetle-kill and cutblock areas could be more pronounced at upper slope locations. Such stand-level findings suggest potential implications for regional-scale groundwater resources that may not manifest for decades or longer.

Hydrogeologic Landscapes of British Columbia

The overviews of published studies shown in Tables 1 and 2 originate from many different physiographic and climatic regions. In order to translate and/or transfer the findings of these published studies, and to help visualize the role of groundwater hydrology in watershed, we present a regional-scale classification of hydrogeologic landscapes for British Columbia (Figure 2). A more complete description and rationale for this classification is provided in the synthesis article by Smerdon et al. (2009).

The mountain peaks, highland plateaus, and valleys that characterize British Columbia have developed over millions of years. The geologic history includes tectonic events and glaciations, which have left behind deposits of sediments and rock formations that form many hydrogeologic settings. To assess the nature of groundwater resources and to begin to assess the potential impacts of forest management practices, an

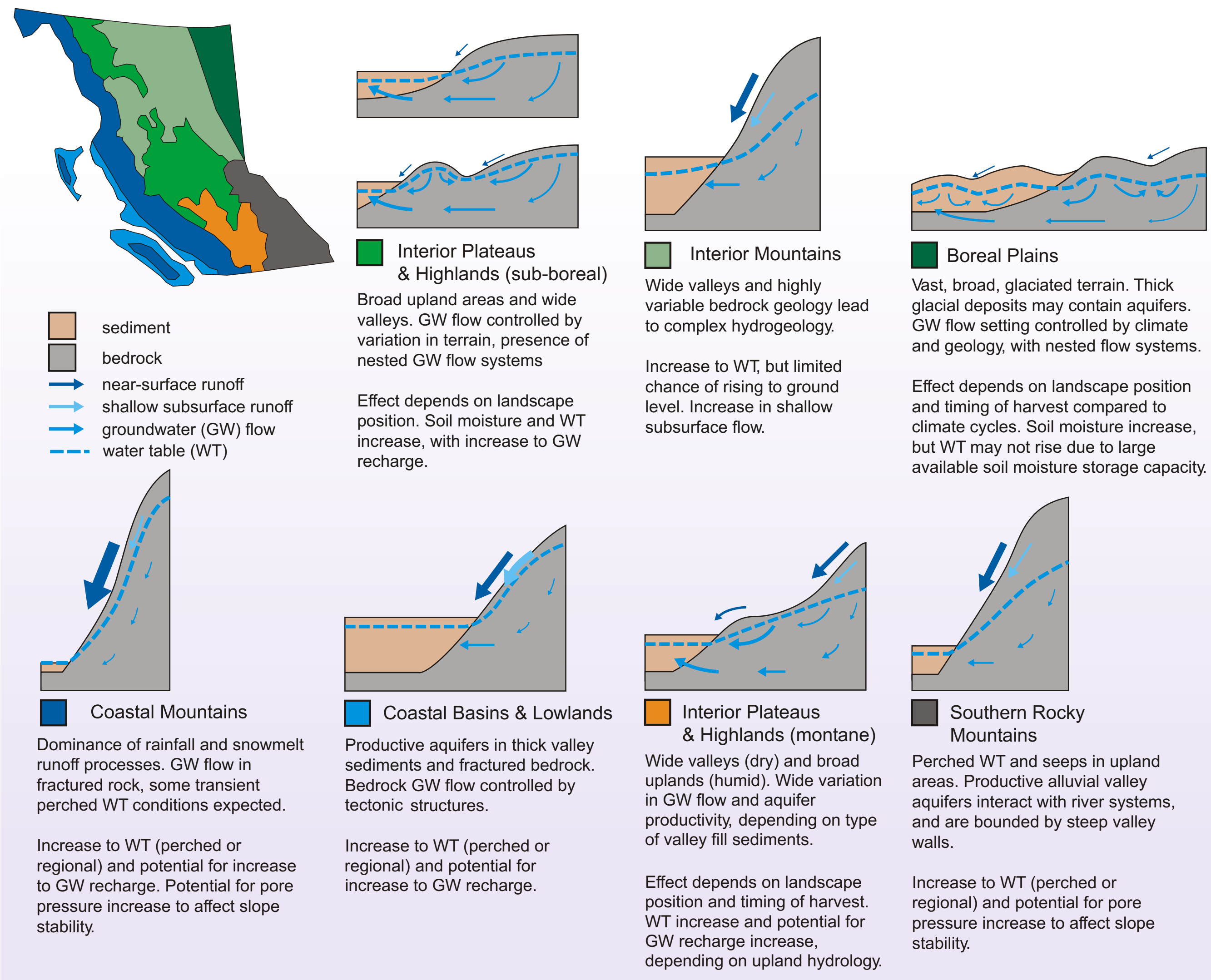

Figure 2. Hydrogeologic landscapes for British Columbia, indicating general variations in depth of the water table and types of groundwater flow systems that may develop. General hydrogeologic characteristics are provided, with hypothetical effects of forest harvest for each unique landscape. The size of the arrows is proportional to the expected magnitude of the relative flux through a given flow path.

understanding of the climatic, physiographic, and geologic setting is critical (Livingstone 1994). Regional hydrogeologic landscapes (such as those illustrated on Figure 2) provide a broad-scale framework and are based on the major physiographic units (Church and Ryder 2007), groundwater regions (Foweraker 1994), and biogeoclimatic zones of British Columbia. These seven hydrogeologic landscapes represent a cross-section of broad-scale groundwater movement for distinct regions in British Columbia, and span a climatic gradient (i.e., from very humid to semi-arid), and topographic gradient (i.e., from steep mountain regions to broad plains).

Each region described in Figure 2 has unique characteristics that control subsurface flow, and within each landscape setting, there will be various types of specific aquifers that also have unique characteristics that could be investigated at a finer level of detail. For the Cordilleran Region, a more formal aquifer characterization has been proposed by Wei et al. (2007), which includes six specific aquifer types. Although the hydrogeologic landscape categories listed on Figure 1 are more general than would be directly applicable for specific forest management investigations, they do provide a basis for describing groundwater flow characteristics and the potential impacts from forest management practices (hypothetical effects of harvest are identified in Figure 1). We envision this framework as a step toward understanding the role of groundwater in watersheds, and as a basis for proposing future collaborative research to narrow the gaps in the knowledge of forest management effects (or other types of land-use change) on groundwater hydrology.

Conclusions

Groundwater is a major component of the hydrologic cycle. Thus,

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groundwater plays some role in watershed processes and is affected by forest management activities and disturbance caused by other land-use or land-cover changes. The consequence of this effect is dependent on the importance of groundwater in overall watershed hydrology, and to ecosystem and human reliance on groundwater. Generally, this reliance is expected to be higher for basins, plains, and lowland areas (e.g., Okanagan Basin), reflecting the presence of thicker sediment deposits (Figure 2), and lower for relatively unpopulated steep highland and mountain areas.

We found that there are very few published studies on the impact of forest harvest and road building on groundwater hydrology. In most cases, a rise in water table can be expected to follow harvest, which will have a range of effects depending on the geology and topography of harvested area and the location of roads and the road construction practices. For wet, steep watersheds like the Coastal Mountains, groundwater effects are expected to be depth limited and there is a reasonable level of understanding of what could happen to groundwater regime (pore pressure increases, additional runoff). For these more humid landscapes, the watershed hydrology is dominated by shallow runoff, as opposed to deeper groundwater systems. For a drier climate, and lower relief terrain, the potential for complex groundwater response increases. On terrain with gentle topography, water table increases can be expected to alter flow systems of varying sizes, which means effects may be readily apparent (in the case of local-scale flow), or concealed within a regional-scale flow system.

Pike and Scherer (2003), Redding and Nickurak (2008), and Redding et al. (2008) have identified that there is need for a better understanding of groundwater in their assessment of knowledge gaps for BC's interior watersheds. We have presented a broad-scale classification of hydrogeologic landscapes for British Columbia in an effort to integrate the available studies on water table rise, on increase to groundwater recharge, and on the effect of these changes to groundwater hydrology. We hope that further research may be directed toward filling knowledge gaps on the process linkages between forest management and groundwater hydrology in these regions, so successful resource planning and sustainable forest management may be achieved. Closing these knowledge gaps will help sustain groundwater resources for future generations.

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Information Note

The BC Freshwater Atlas

Malcolm Gray

The quality of British Columbia's water is a barometer that reflects the environmental, economic, and social well-being of our province. British Columbia's burgeoning population, industrial and agricultural growth, and the potential impacts of climate change are only increasing the value of our water resources. The Freshwater Atlas has been developed as a freely and publicly available tool to ensure freshwater resources in this province are sustained for future generations.

What is the Freshwater Atlas?

The Freshwater Atlas is a standardized dataset for mapping the province's hydrological features. It represents a significant improvement over the previous 1:50 000 scale Watershed Atlas because it is derived from the province's more detailed 1:20 000 scale topographic base maps (TRIM). Another major improvement is the specific coding of all stream segments and corresponding watersheds (30 ha average size) establishing an unambiguous upstream-downstream relationship for all features. The atlas defines watershed boundaries by height of land and provides a connected three-dimensional network of streams, lakes, and wetlands.

Each stream in the province has its own watershed (the land drained by that stream), but it is also linked to other streams and watersheds that it flows from and to. The Freshwater Atlas allows you to connect a stream to both its tributaries and the watersheds associated with them (Figure 1).

The atlas was designed to be the authoritative source for mapping freshwater features in British Columbia. It provides a consistent coding system that ensures the province's various freshwater-related inventories are tied to a common base. Watersheds are bounded by heights of land, which provide the authoritative reference for many administrative boundaries and land tenures. The Freshwater Atlas offers a connected network that serves as the foundation for sophisticated analysis and modelling.

How was the Freshwater Atlas developed?

The basic source data for the Freshwater Atlas were the rivers, streams, lakes, wetlands, and man-made waterbodies as identified on the 1:20 000 scale TRIM base map. This input information, while very consistent, well-specified, and quality-assured (QA), was only available on a map sheet basis (7027 tiles to cover BC). In addition, most features in TRIM were simple line work and did not form complex features such as lake polygons or stream networks. In the Freshwater Atlas, the stream network is connected through lakes, double line rivers, and wetlands allowing water flow to be mapped. The stream network is connected through glaciers, but glaciers are not as tightly integrated with the stream network as are lakes, wetlands, or double line rivers.

TRIM 1 base mapping (air photo date: late 1980s) was used to develop the atlas to ensure a consistent scale across the province. TRIM 2 data were not used because the greater detail (1:10 000 scale) only exists for half of British Columbia. As some attributes (e.g., stream order and magnitude) are scale-dependent, combining the two TRIM scales would have introduced inconsistencies in the atlas. In addition, scale differences across map sheet boundaries would result in a lack of continuity and connectedness for streams.

Each stream in the province has its own watershed (the land drained by that stream), but it is also linked to other streams and watersheds that it flows from and to. The Freshwater Atlas allows you to connect a stream to both its tributaries and the watersheds associated with them (Figure 1).

While the level of detail available is more than adequate for the majority

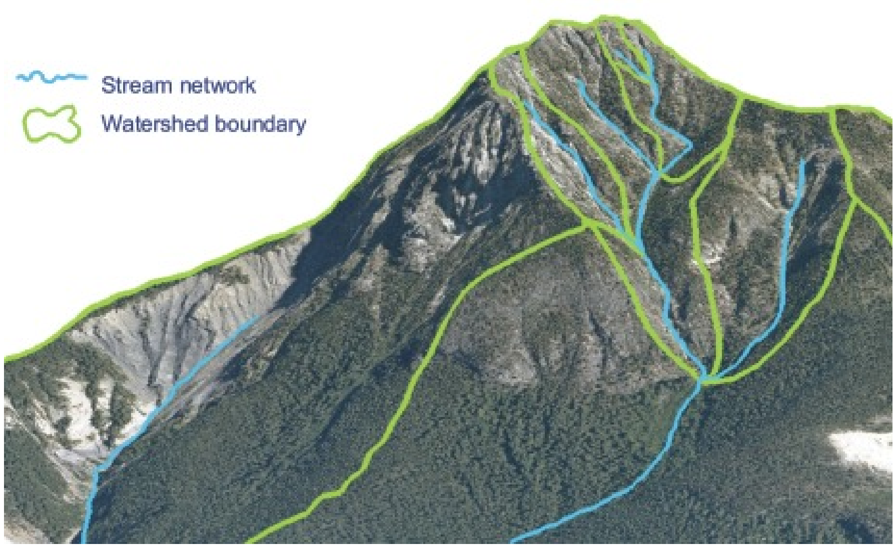

Figure 1. Conceptualization of watershed atlas mapping units.

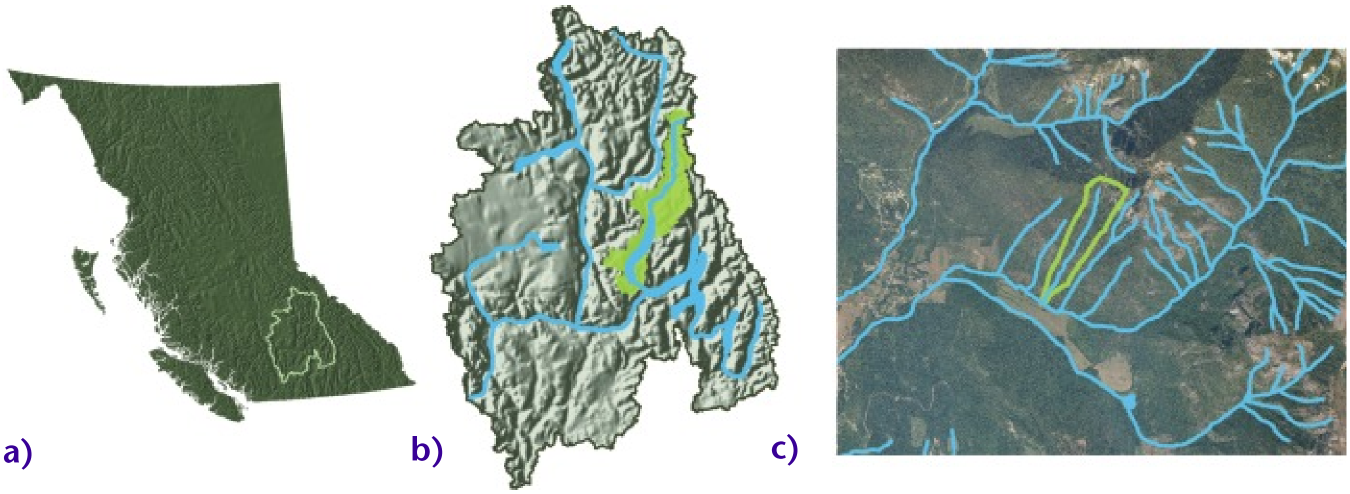

Figure 2. Scales of application of the Freshwater Atlas. The outline of (a) the Thompson River watershed within the Province of BC, (b) sub-basins of the Thompson River watershed including the Adams River in green and, (c) a sub-basin of the Adams River watershed.

of applications (BC is divided into 3 million watersheds), GeoBC is continuing to improve the product through the development of a method to add the greater detail available in TRIM 2. However, the current codes will be the standard index for linking inventory information both now and in the future.

One challenge for GeoBC is to quantify on-the-ground changes, mapped between the TRIM 1 and TRIM 2 products. Some features, such as glaciers, are known to have undergone significant change, and other hydrologic features undergo continual change (i.e., sand bars and islands in large rivers). GeoBC will be addressing this during 2009/10, beginning with an evaluation of the amount of change over time. The expectation is that from a provincial perspective, at the 1:10 000 scale, there is very little change, but this remains to be determined.

Creating the atlas involved many years of effort. Mappers had to ensure continuity across map sheet boundaries, construct "skeleton" lines through waterbodies to explicitly connect the hydrologic network, infer the hydrologic connections for isolated waterbodies, and repeatedly create and QA the hydrologic flow through the network. This last step involved knowledgeable staff conducting a major manual checking process of the hydrologic network to resolve flow contradictions.

In developing the atlas, watershed codes were assigned to every stream segment following a method that built upon, and improved, the existing 1:50 000 Watershed Atlas coding system. In addition to the traditional code, a second code was generated at every confluence for both the tributary and mainstem. The watershed codes alone, allow the correct upstream/downstream relationship for all stream segments and associated features to be determined without complicated spatial analysis (i.e., independent of a geographic information system [GIS]).

Three-dimensional elevations were assigned to the hydrologic network and conditioned to be monotonically decreasing downstream. This was more than just smoothing out the +/–5 m vertical measurement difference in TRIM as many large lakes have a surface-elevation difference of tens of metres, the result of photography taken in different seasons and years.

Once a complete and consistent hydrologic network was developed, the topography (constrained by the hydrologic network) was used to delineate the watershed of each stream segment. These watersheds are small, on average 30 ha, with every confluence having its local watersheds determined. The local watersheds allow the troublesome long and narrow watershed polygons present in the 1:50 000 scale version to be subdivided and eliminated.

The hydrologic network was repeatedly quality assured throughout its production. Extensive consistency checks were conducted for all components (e.g., watersheds, waterbodies, and place names). The end result is a consistent, province-wide, three-dimensional, freshwater network, mapping the hydrological features of BC at a scale of 1:20 000.

How many lakes are there in the province?
386 049

What is the total area of lakes in the province?
22 434 km²

What is the length of the province's coastline?
37 902 km

What is the total length of streams and rivers in the province?
1 955 540 km

How many wetlands are there in the province?
378 426

What is the total area of wetlands in the province?
41 143 km²

Continued on page 26

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What information does the Freshwater Atlas contain?

The Freshwater Atlas has the following features:

- Coastline, major rivers, streams, and all tributaries mapped at 1:20 000 scale
- Obstructions: dams, waterfalls, and rapids
- Waterbodies: lakes, wetlands, and glaciers
- Coastal bays and inlets
- 20 000 named features (from the BC Gazetteer)
- 3 million watersheds, average size 30 ha
- Watershed code giving upstream/downstream relationships for all features

Names of many water features are accessible and coding within the data allows you to identify connected features and map upstream and downstream relationships. As there have been changes to the size of some glaciers since the original mapping in the 1980s, there will be some error in glacier extent. The magnitude of glacier errors and the potential for updating will be assessed in 2009/10.

What can you do with the Freshwater Atlas?

The Freshwater Atlas also allows you to:

- map water features and their associated watersheds;
- conduct analyses at a province-wide level;
- identify connected watersheds, streams, rivers and lakes at regional levels; and/or
- examine an individual stream's watershed for local planning.

What types of questions can be answered?

The Freshwater Atlas can be used to answer questions such as:

- How many lakes, wetlands, glaciers, and reservoirs are in my study area, and what size are they?
- Which streams, lakes, and wetlands are either downstream or upstream of a development that is planned for a particular local area?
- How many watersheds occur in a regional planning unit, what are their areas, and what is the total area of the land base they occupy?

These types of questions can be answered for the whole province, a region, or a single watershed.

Names of many water features are accessible and coding within the data allows you to identify connected features and map upstream and downstream relationships. As there have been changes to the size of some glaciers since the original mapping in the 1980s, there will be some error in glacier extent. The magnitude of glacier errors and the potential for updating will be assessed in 2009/10.

How can the Freshwater Atlas's stream network be used?

The Atlas lets you link environmental information to the province's network of streams, lakes, and rivers by location for applications such as:

- Water management and water-use planning
- Display of fisheries data
- Hydrological modelling
- Locating water features by name
- Emergency preparedness: Identify communities downstream of a dam or resources in the path of a chemical spill

The Freshwater Atlas provides a foundation for studying factors that influence salmon habitat in British Columbia. It facilitates the integration of the following types of information:

- Spawning habitat maps
- Locations of salmon-bearing streams and lakes
- Water-quality monitoring stations and stream flow data
- Upstream and downstream land uses
- Obstructions blocking fish passage
- Recreational and commercial harvest statistics
- Salmon-escapement statistics

How can the Freshwater Atlas help our understanding of the land base?

Information from a variety of disciplines can also be linked or summarized by the watersheds within the atlas. This lets us examine the potential impacts of both human activities and natural phenomena on the landscape.

Statistics for each watershed can be generated to quantify land-use types or density values. These can provide useful indicators that help us to monitor the conditions within either an individual watershed or to compare watersheds within either a region or throughout the entire province.

How do I find out more information?

To find out more information about the Freshwater Atlas or to download this public dataset go online at: *http://aardvark.gov.bc.ca/apps/dwds/home.so* and search on the Freshwater Atlas' old acronym "CWB" (searching on Freshwater Atlas will work soon, the name change is being implemented March 2009).

For more information, contact:

Malcolm Gray
GeoBC, INTEGRATED LAND MANAGEMENT BUREAU
(250) 952-6573
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Information Note

University of Victoria Programs in Natural Restoration for Working Professionals

The University of Victoria is offering two certificate and diploma programs in natural restoration that will be of interest to natural resource professionals who are working in, or would like to extend their expertise in, environmental resource management.

The Restoration of Natural Systems Certificate and Diploma is an award-winning program which has been operating for 12 years to serve the needs of students new to the field of restoration. The program takes a holistic approach, combining science and social science. Graduates emerge from this program with broad-based knowledge of restoration techniques and information about diverse ecosystems in British Columbia, and with a conceptual framework for restoration projects which is rooted firmly in the context of community. Courses are designed for people who need a flexible study format and are offered through on-campus immersion and distance education.

For summer 2009, we will be offering the following courses:

- Field Study in Environmental Restoration
- Advanced Principles and Concepts of Ecological Restoration
- Forest Restoration and Sustainable Forestry
- Ecorestoration Strategies: Case Studies

For more information, see www.uvcs.uvic.ca/restore

The Native Species and Natural Processes Certificate is a new program specifically designed with professional development needs in mind. When fully implemented, the program will be offered in a distance format with courses offered on an annual rotation. The program is intended for professionals working in restoration or related fields and offers advanced level training in such topics as systems approaches to restoration, invasive species, and the built environment.

Our next course, which will be offered in 2009, will be Invasive Species Management (Dates TBD).

For more information, see www.uvcs.uvic.ca/nature

Both of these programs are offered in partnership between the School of Environmental Studies and the Division of Continuing Studies. You can take a few courses or take the full program.

For more information, contact:

Janet Pivnick,
jpivnick@uvcs.uvic.ca
(250) 721-8463

UPDATE

Announcements

New Watershed Management Extension Specialist

Kevin Bladon joined FORREX this fall as a Watershed Management Extension Specialist. In partnership with the University of British Columbia–Okanagan, he and teammate Todd Redding are responsible for identifying information needs, and developing and co-ordinating extension programming and services related to sustainable watersheds. Kevin is also involved in conducting research and in synthesizing and integrating research results/knowledge into sound and practical approaches to solve the complex watershed management challenges facing resource managers. Prior to joining FORREX, Kevin worked at the University of Alberta as an Ecohydrologist on the Southern Rockies Watershed Project in the eastern slopes of Alberta's Rocky Mountains. This work provided him with an extensive background in natural (wildfire and mountain pine beetle) and anthropogenic (conventional and salvage logging) disturbance impacts on water quantity, water quality, and aquatic ecology. He has also been employed as a natural resources consultant, working closely with various stakeholders to develop sustainable solutions to watershed management issues. Kevin has a PhD in ecohydrology from the University of Alberta, which addressed tree–water relations and microclimate change. Kevin is based in Kelowna at the University of British Columbia–Okanagan and can be reached at:

Email: Kevin.Bladon@forrex.org
Phone: (250) 807-9516

Okanagan Sustainable Water Strategy

The Okanagan Sustainable Water Strategy is designed to build on the 1974 Okanagan Basin Study, a joint federal/provincial initiative to develop a comprehensive plan for the development and management of water resources in the Basin. The 1974 study is the only Basin-wide study completed to date for the Okanagan. A subsequent Basin-wide study of surface water and groundwater resources—the Water Supply and Demand Project—was initiated in 2004 and is expected to be completed in late 2009. The goal of the Water Supply and Demand Project is to provide the best estimate of present and future water needs and availability, taking into account present water use, population growth, climate change, land use change, preservation of the environment, and other factors. Once complete, the Water Supply and Demand Project will be complementary to the Sustainable Water Strategy. The strategy articulates the vision and provides direction whereas the supply and demand project provides the data needed to develop and implement strong water management practices.

Full report:
http://www.obwb.ca/fileadmin/docs/osws_action_plan.pdf

Executive Summary:
http://www.obwb.ca/fileadmin/docs/osws_executive_summary.pdf

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Recent FORREX Publications:

LINK Volume 10, Issue 3 is now available at:

http://www.forrex.org/publications/link/link.asp

BC Journal of Ecosystems and Management Special Issue:

Mountain Pine Beetle: From Lessons Learned to Community-based Solutions (Conference Proceedings) Full Proceedings available from

http://www.forrex.org/publications/jem/ISS49/vol9_no3_MPBconference.pdf

Watershed Management Related Papers and Abstracts:

Redding, T., R. Winkler, P. Teti, D. Spittlehouse, S. Boon, J. Rex, S. Dubé, R.D. Moore, A. Wei, M. Carver, M. Schnorbus, L. Reese-Hansen, and S. Chatwin. 2008. **Mountain pine beetle and watershed hydrology**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):33–50.

Teti, P. 2008. **Sampling secondary structure on novel aerial photographs**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):98–100.

Dubé, S. and J. Rex. 2008. **Hydrologic effects of mountain pine beetle infestation and salvage-harvesting operations**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):134.

Schnorbus, M. 2008. **Quantifying the hydrologic impacts of mountain pine beetle and associated salvage operations in the Fraser River watershed**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):135.

Teti, P. and R. Winkler. 2008. **Snow hydrology and solar radiation in growing and deteriorating pine stands**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):136–138.

Weiler, M., K. Rosin, and C. Scheffler. 2008. **Development of a hydrologic process model for mountain pine beetle affected areas in British Columbia**. *In* Mountain Pine Beetle: From Lessons Learned to Community-based Solutions Conference Proceedings, June 10–11, 2008. BC Journal of Ecosystems and Management 9(3):139.

FORREX Series

Gayton. D. 2008. **Impacts of climate change on British Columbia's biodiversity: A literature review.**

FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. FORREX Series 23.

URL: http://www.forrex.org/publications/forrexseries/fs23.pdf

Upcoming Events

Conserving Wetlands in British Columbia

May 28–29, 2009
Revelstoke, BC

The Columbia Mountains Institute is organizing a conference on conserving wetlands in British Columbia. Reservoir creation, settlement, agricultural activities, transportation corridors, and other factors have eliminated many wetland complexes or diminished their natural form and function. At this two-day event we will examine the past, present, and possible future extent of wetlands; the reasons for these changes; and how a combination of conservation, management, restoration, stewardship strategies, and on-the-ground projects can improve the ecological values of British Columbia's wetlands

For further information on the conference and to submit an abstract, please contact Jackie Morris (office@cmiae.org) or visit: *http://www.cmiae.org*

2nd International Conference on Forests and Water in a Changing Environment

September 14–16, 2009
Raleigh, North Carolina, US

Growing concerns over watershed degradation, water scarcity, and ecosystem sustainability due to climate change require new approaches to managing forest water resources. Unfortunately, little science-based guidance is available for forest managers and policy makers adapting to climate change. The goal of this symposium is to provide a forum for experts from around the world on ecohydrology, restoration ecology, forest ecology, watershed management, and global change sciences to share knowledge and research experiences, and to develop long-term international collaborations on watershed research. Please visit the conference website for updates: *http://www.sgcp.ncsu.edu:8080/*

Recent Publications of Interest:

Beechie, T. et al. 2008. **Setting river restoration priorities: A review of approaches and a general protocol for identifying and prioritizing actions.** North American Journal of Fisheries Management 28: 891–905.

Bladon, K.D. and Silins, U. 2008. **Linking silviculture to watershed management**. Canadian Silviculture. August 2008: 7–10.

Dawson, R., A.T. Werner, and T.Q. Murdock. 2008. **Preliminary analysis of climate change in the Cariboo-Chilcotin area of British Columbia**. Pacific Climate Impacts Consortium.

URL: http://www.pacificclimate.org/docs/publications/CaribooChilcotinClimate.08Sept08.pdf

Floyd, W. and Weiler, M. 2008. **Measuring snow accumulation and ablation dynamics during rain-on-snow events: Innovative measurement techniques**. Hydrological Processes 22: 4805–4812.

Hamilton, L.S. 2008. **Forests and Water: A thematic study prepared in the framework of the Global Forest Resources Assessment.** FAO Forestry Paper 155.

http://www.fao.org/docrep/011/i0410e/i0410e00.htm

Moore, R.D., S.W. Fleming, B. Menounos, R. Wheate, A. Fountain, K. Stahl, K. Holm, and M. Jakob. 2009. **Glacier change in western North America: Influences on hydrology, geomorphic hazards and water quality**. Hydrological Processes 23(1): 42–61.

Nordin, L.J., J.F. Rex, D.A. Moloney, and P.J. Tschaplinsky. 2008. **Standardized approaches in effectiveness monitoring programs and regional relevance: Lessons from the Bowron River Watershed Riparian Evaluation Project**. Canadian Journal of Forest Research 38: 3139–3150.

Rex, J.F. and Petticrew, E.L. 2008. **Delivery of marine-derived nutrients to streambeds by Pacific salmon**. Nature Geoscience 1: 840–843.

Richardson, J.S. 2008. **Aquatic arthropods and forestry: effects of large-scale land use on aquatic systems in Nearctic temperate regions**. Canadian Entomologist 140: 495–509.

Roni, P., K. Hanson, and T. Beechie. 2008. **Global review of the physical and biological effectiveness of stream habitat rehabilitiation techniques**. North American Journal of Fisheries Management 28: 856–890.