Research Report

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Snow cover extent during spring snowmelt in the south-central interior of British Columbia

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Abstract

The H60 contour elevation (i.e., elevation above which 60% of the watershed lies) is commonly used in hydrologic impact assessments of snowmelt-dominated watersheds in the interior of British Columbia. The H60 concept assumes that the upper 60% of a mountainous watershed is snow-covered and is contributing meltwater during the time of peak flow; thus, peak streamflow is assumed to be more sensitive to forest harvesting above the H60 contour elevation. However, the concept has not been well-verified by field data. This study tested the H60 concept for the Mission Creek watershed in the Okanagan region of British Columbia. Snowlines were mapped during spring freshet (snowmelt runoff) for 5 years (1999–2003). These data were analyzed with corresponding runoff data to determine, for each year, the snowline that best represents the lower extent of snow cover upon commencement of the peak flow period. It was found that, on average, 38% of the Mission Creek watershed was snow-covered at the start of the peak flow period, which represents an average contour elevation of 1520 m; the H60 elevation is 1300 m. These results suggest that the H60 concept overestimates the extent of snow cover during the spring peak flow period and, therefore does not reasonably represent the snow-sensitive zone of the Mission Creek watershed. This may be important in the assessment of potential forest harvesting impacts in the watershed.

KEYWORDS: *forest development, H60, hydrologic assessment, Mission Creek, Okanagan, peak flow, runoff, snow-covered area, snowline, snow-sensitive zone, spring freshet, watershed.*

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Introduction

Throughout the interior of British Columbia, the Interior Watershed Assessment Procedure (IWAP; B.C. Ministry of Forests 2001) has been used as a tool for monitoring and managing the impacts of forest development on watershed conditions and water supply (quantity, quality, and timing). Harvest level within the snow-sensitive zone of watersheds (area covered by snow and contributing to flows during the peak flow period) has been monitored to minimize potential harvesting impacts. Knowledge of the location of the snow-sensitive zone is important. It is the portion of the watershed that generates the peak flows and, thereby, has the greatest potential influence on downstream flows. Increases in the size and duration of peak flows are of concern to forest managers since these flows can alter sediment transport capacity and channel morphology (MacDonald and Stednick 2003). Any activities in the snow-sensitive zone that affect snowmelt and subsequent runoff have the potential to influence peak flow levels, channel morphology, and water quality (Cheng 1989; Olsen *et al.* 1997; Whitaker *et al.* 2002; MacDonald and Stednick 2003).

Studies have shown that forest canopy removal increases snow accumulation, snowmelt rates, and total water yield (Stednick 1996; Marks *et al.* 1998; Storck *et al.* 1999; Winkler *et al.* 2005). Winkler *et al.* (2005) found that April 1 snowpacks in south-central British Columbia had, on average, 23% less snow water equivalent (SWE) in a mature spruce-fir stand than in an adjacent clearcut. Average snowmelt rates in the mature stand were less than half (0.4 times) those in the clearcut. Canopy removal also advances the timing of snowmelt and can, consequently, synchronize or desynchronize high flows (Troendle and King 1985; Troendle *et al.* 2001; Schnorbus and Alila 2004).

Since enactment of the Forest Practices Code (FPC) of British Columbia in 1995, the H60 contour elevation (i.e., elevation above which 60% of the watershed lies) has been used to represent the lower extent of the snow-sensitive zone for watersheds in the interior of British Columbia. The H60 concept assumes that the upper 60% of a mountainous watershed is snow-covered and is contributing meltwater during the time of peak flow. Peak flows are, therefore, assumed to be more sensitive to forest harvesting above the H60 elevation. This concept was initially based, in part, on the results of a study in Colorado that occurred between 1946 and 1953 (Garstka *et al.* 1958). Few empirical studies have investigated the concept. One exception is Gluns (2001) who analyzed snowlines and runoff in two small watersheds (Redfish and Laird Creeks) in the West Arm Demonstration Forest near Nelson, B.C., to confirm the applicability of the H60 concept. Gluns found that an H65 was most applicable, but concluded that the difference was not significant and may be within the error of interpretation.

This research improves our understanding of the spatial extent of snow cover during the spring peak flow period and helps identify areas where forest harvesting is most likely to affect snow processes and downstream peak flows.

Several studies have investigated the elevational relationship of forest harvesting impacts on runoff from a modelling approach. Schnorbus and Alila (2004) applied the Distributed Hydrology Soil Vegetation Model (DHSVM) to Redfish Creek watershed and found that harvesting above the H60 elevation significantly increased peak flows, whereas harvesting below the H60 did not. They also found that peak flow increases were more severe with increasing proportion of harvest area above the H60. A rationale supporting this pattern is that peak flows are derived from a synchronized accumulation of snowmelt runoff from the upper portions of the watershed where harvesting impacts on snowmelt may also result in peak flow impacts. Moreover, the impacts of harvesting on snowmelt in the lower portions of the watershed are desynchronized in time with the occurrence of peak flows.

Also using the DHSVM, Whitaker *et al.* (2002) modelled forest harvesting and runoff in the Redfish Creek watershed to evaluate the sensitivity of mid-May to mid-June high flows to logging in different elevation bands of the watershed. The results suggested that the relationship between harvest elevation and peak flow change is more complex than suggested in the IWAP. The simulation study showed that the area above the H80 elevation (i.e., elevation above which 80% of the watershed lies) rather than the H60, was important for generating snowmelt peak flows. Cutblock location above the H80 was relatively unimportant in influencing peak flows. Increasing harvest levels in the middle portions of the watershed (between the H40 and the

H80) led to instantaneous flow increases of up to 22% with 22.4% of the watershed harvested. The upper 40% of the Redfish Creek watershed is alpine or subalpine and, therefore, the potential impact on flow from harvesting in the upper portion is reduced compared to the potential impact from harvesting in the densely forested middle portion of the watershed. This pattern may not be consistent in watersheds that are densely forested to the highest elevation where, due to the effects of forest cover removal on snow accumulation and melt patterns, the greatest impact on flow is expected from harvesting at higher elevations.

Since they are not empirical, these modelling studies neither confirm nor reject the validity of the H60 concept. However, the Schnorbus and Alila (2004) results demonstrate consistency with Gluns' (2001) findings. The Whitaker *et al.* (2002) results suggest that the H80 contour elevation may be more relevant for snowmelt-generated peak flows. The findings of both modelling studies suggest that harvesting above each respective contour elevation (either H60 or H80) increases peak flows, whereas harvesting below these elevations has only minimal impacts on peak flows.

The Gluns (2001) research was the first of its kind in British Columbia and provided an initial step to testing the H60 concept for snowmelt-dominated alpine/subalpine watersheds in southeast British Columbia. However, Gluns recognized that the findings were specific to the type of hydrologic system studied (i.e., snowmelt-dominated runoff, large range in elevation, and increase in SWE with elevation) and that the results might not necessarily apply to other regions of the province with different watershed physiography. On this basis, several snowline studies were initiated in the south-central interior Okanagan plateau of British Columbia to better understand the snow-sensitive zones of local watersheds. Spatially distributed snow cover and hydrometric data were gathered for several watersheds over at least five consecutive years. The results of these studies have been used to improve forest planning through increased knowledge of the hydrologic systems and the potential impacts of forest harvesting.

This research report presents the data and results for the Mission Creek watershed in the Okanagan region for the years 1999–2003. We report on the delineation of the snow-sensitive zone for the watershed based on the timing of the peak flow period. The Mission Creek watershed study tested the H60 concept. This research improves our understanding of the spatial extent of snow cover during the spring peak flow period and helps identify areas where forest harvesting is most likely to affect snow processes and downstream peak flows.

Study Area

The Mission Creek watershed is located in the central Okanagan in the south-central interior of British Columbia (Figure 1). The Mission Creek watershed was selected mainly because of the available snowline data (1999–2003) and because of the availability of Water Survey of Canada (WSC) hydrometric data from gauging stations located within the watershed.

The climate within the Okanagan region is considered semi-arid continental, as it lies in a rain shadow east of the Coast Mountain Range. Average annual precipitation at the Kelowna airport[1] is 381 mm with 45% falling between November and April. At the Mission Creek snow pillow monitoring site[2] at an elevation of 1780 m, the annual maximum SWE averages approximately 500 mm and usually occurs in mid- to late April.

For this study, we defined the Mission Creek watershed as the area draining into Mission Creek upstream from the Black Mountain Irrigation District (BMID) water intake. The watershed area above the intake is 601 km^2; the total Mission Creek watershed area above the mouth at Okanagan Lake is 811 km^2. The Mission Creek watershed, as defined for this study, ranges in elevation from 648 to 2222 m. The average discharge of Mission Creek near the East Kelowna hydrometric station[3] is 6.3 m^3/s (0.67 mm/day of runoff). During the 2002 Mission Creek IWAP, approximately 23% of the watershed area had been harvested and the equivalent clearcut area (ECA) was 16%. Equivalent clearcut area is a calculation of the portion of the watershed cleared or burned while accounting for potential hydrologic recovery resulting from forest regeneration (B.C. Ministry of Forests 2001). The H60 elevation is 1300 m.

1 Environment Canada Station No. 1123970.
2 B.C. Ministry of Water, Land and Air Protection Station No. 2F05P.
3 WSC Station No. 08NM116.

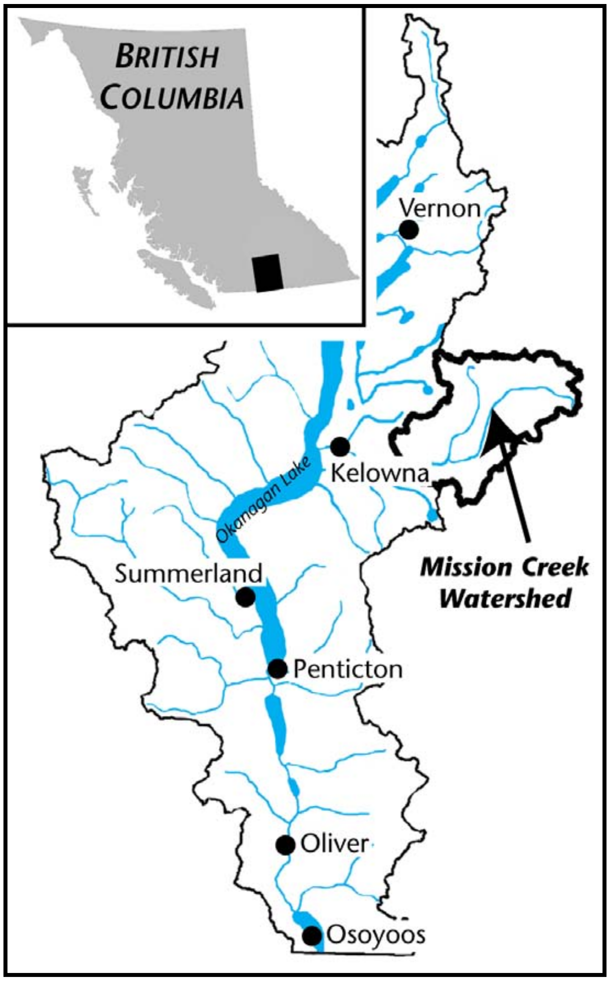

FIGURE 1. Location of the Mission Creek watershed within the Okanagan basin.

Methods

The research approach in this study was similar to that developed by Gluns (2001). Between 1999 and 2003, the snowline was mapped between two and five times during the spring freshet, primarily in the month of May. The timing of the snowline surveys was based on mapping the snowline location approximately midway through the rising limb of the hydrograph and at the time of the actual peak flow. This required subjectively predicting, on an ongoing basis, the timing of the peak flow using climate and snowpack data. The snowline surveys involved flying over the watersheds in a fixed-wing aircraft and delineating the lower extent of continuous snow cover on forest cover maps. Photographs using a 35 mm still camera were used to refine the snowline mapping. For analysis, the final snowlines were digitized in ArcGIS and the area above each snowline was calculated. The total number and frequency of surveys was controlled largely by the availability of funding each year.

By analyzing the dates of the snowline surveys with the hydrometric data, we determined an annual peak flow snowline that represented the lower extent of snow cover at the start of the peak flow period for each year. Note that although the term *annual peak flow snowline* is used, it actually represents the snowline at the start of the peak flow period and not the snowline at the time of the maximum flow (Figure 2). This analysis required several steps. The hydrometric data were plotted from March 1 to August 31 of each year between 1999 and 2003 to determine the timing and magnitude of the annual peak flow. The onset of the peak flow period was determined by adapting the cumulative-departure method from Cayan *et al.* (2001). The method identifies the day when the cumulative departure from a particular year's mean flow is most negative and is equivalent to finding the day after which most flows are greater than average. In the current study, spring freshet was assumed to begin when runoff first exceeded the average runoff for the period of continuous record (1967–2003) for Mission Creek (0.67 mm/day) and end when the runoff first subsided below the 1967–2003 average runoff after the peak flow. The selection criteria are shown in Figure 2.

For the years 1999–2003, spring freshet commenced between April 10 and April 26 and terminated between June 28 and July 23. The average duration was 88 days with a range of 67–97 days. The spring freshet average runoff was determined individually for each annual freshet period. For each year, the peak flow period was assumed to begin at the start of at least five consecutive days with the daily runoff exceeding the average runoff for the annual spring freshet period. For each year, the snowline best representing the lower extent of the snow-sensitive zone was established as the snowline mapped nearest the date of the onset of the peak flow period. The rationale for this selection process is that channel morphologic changes can occur not only at the time of peak flow, but throughout the period of high flow (MacDonald and Stednick 2003). The method also provides an objective approach for determining the onset of the peak flow period for each year of data.

Two methods were used to determine a revised H-value (i.e., snow-sensitive zone) based on the 5 years of snowline and discharge data. In the first method, the H-value was determined based on the average of the watershed areas lying above the five annual peak flow snowlines (Figure 2, Figures 3A and 3B; Table 1). In the second method, the H-value was determined based on

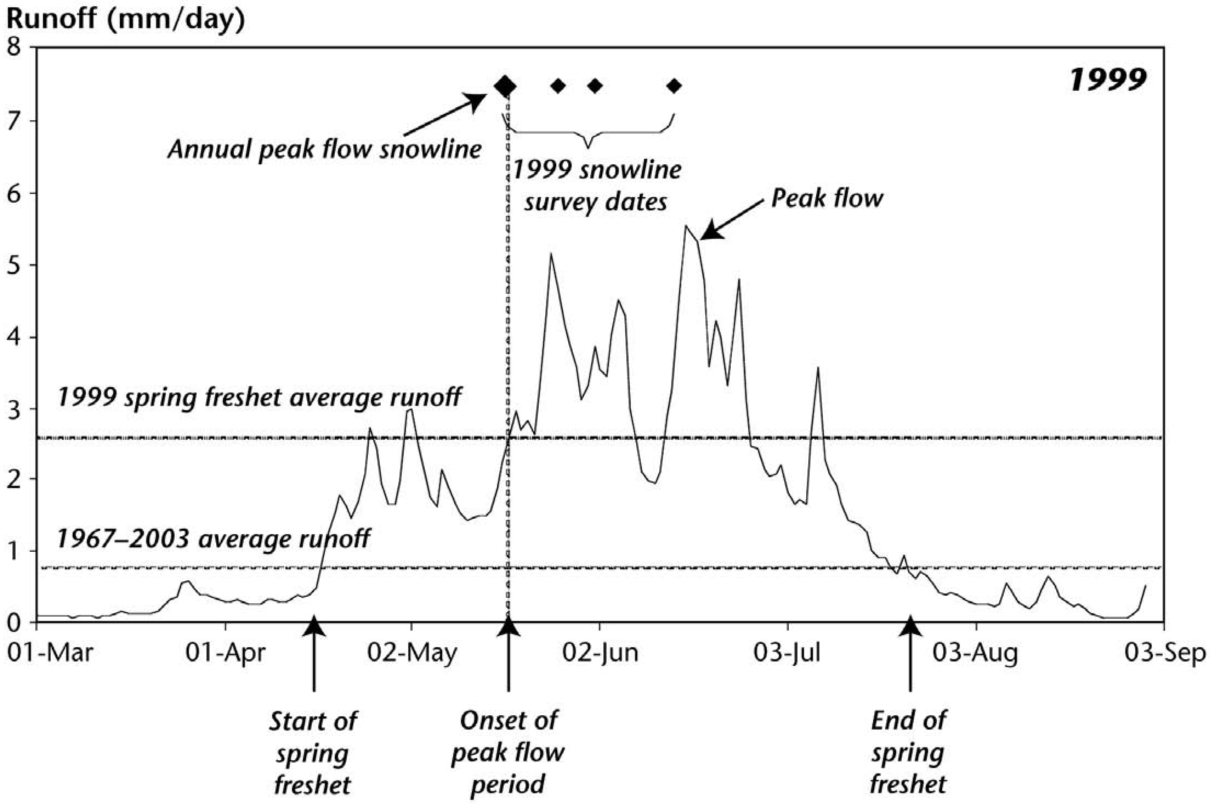

FIGURE 2. Spring freshet hydrograph for 1999 for Mission Creek near East Kelowna (WSC Station No. 08NM116) and snowline survey dates (diamond symbols). The figure illustrates criteria for determining the spring freshet period, the onset of the peak flow period (vertical line), and the survey date of the snowline selected to represent the conditions at the start of the peak flow period (i.e., annual peak flow snowline; large diamond).

the portion of the watershed area covered by snow during each snowline survey (16 data points in total) and the 1999–2003 average daily runoff plotted through time (Figure 4). For the second method, a best-fit line was fitted to the 1999–2003 snow cover data (i.e., a snow cover depletion curve); the average onset date of the peak flow periods was also plotted to determine the corresponding snow-covered portion of the watershed. In addition, the average survey date of the 1999–2003 annual peak flow snowlines was plotted for comparison to the timing of the average onset date of the peak flow periods.

One might consider the second method to be a frivolous exercise since both methods used snow-covered areas from the same dataset; however, the first method is potentially biased by the frequency of snowline surveys and by the selection of annual peak flow snowlines. In contrast, the second method is not directly influenced by the frequency of snowline surveys, as it incorporates all snowline surveys. As a result, the second method provides a check on the first method for determining a revised H-value.

TABLE 1. Watershed area above each mapped snowline and respective portion of the watershed snow-covered. The ‘x’ indicates the selected annual peak flow snowline.

Year	Survey date	Area above snowline (km^2)	Area above snowline (%)	Selected as annual peak flow snowline
1999	May 17	217	36	x
	May 26	178	30	
	June 1	148	25	
	June 14	123	20	
2000	May 5	310	52	
	May 19	181	30	x
	May 25	154	26	
	June 1	133	22	
	June 15	101	17	
2001	May 2	428	71	
	May 11	254	42	x
	May 31	140	23	
2002	May 13	319	53	x
	May 27	184	31	
2003	May 13	193	32	
	May 29	173	29	x
H60		*361*	*60*	
Watershed		*601*	*100*	

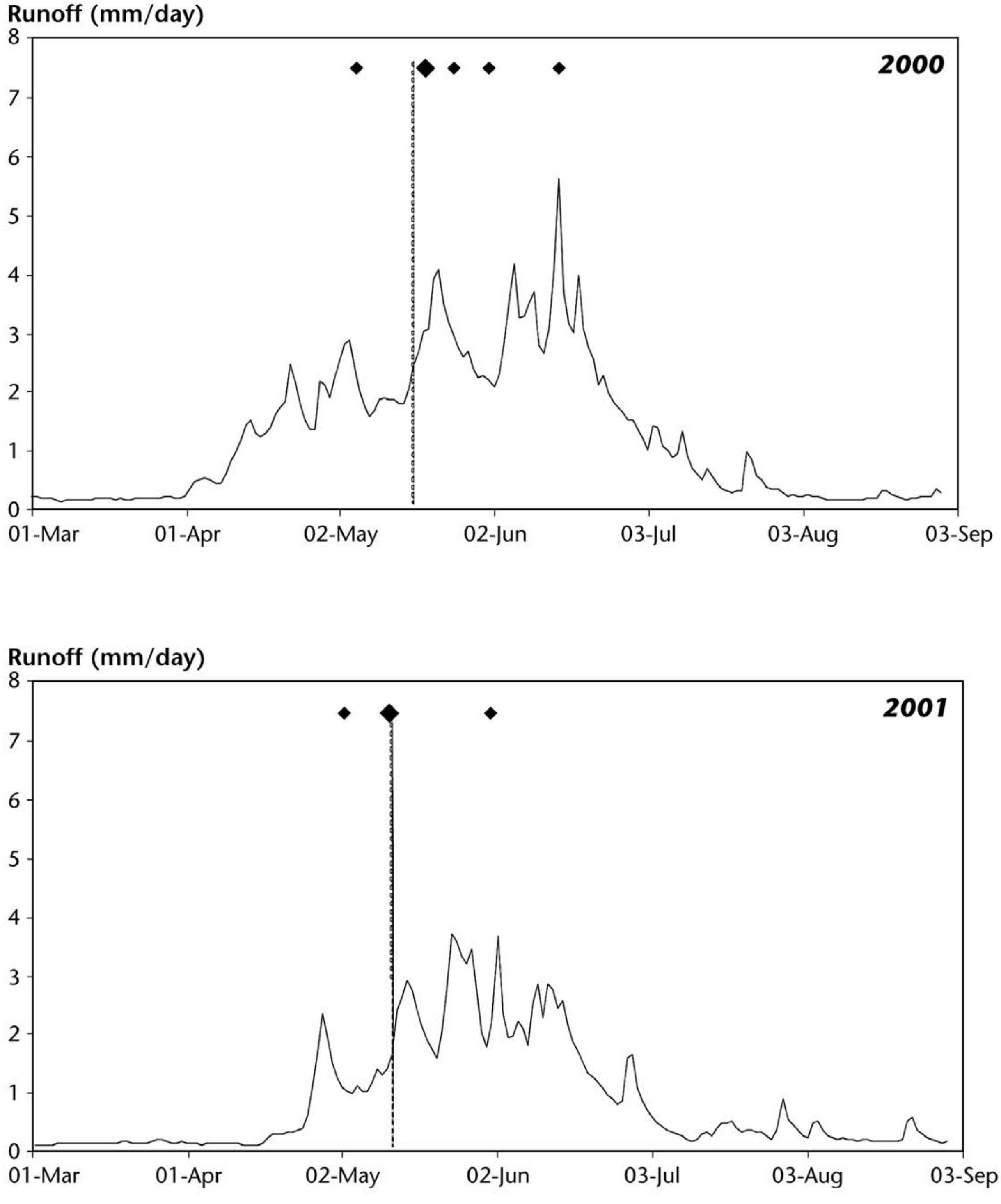

FIGURE 3A. Spring freshet hydrographs for 2000–2001 for Mission Creek near East Kelowna (WSC Station No. 08NM116) and snowline survey dates (diamond symbols). The large diamond indicates the snowline selected to represent conditions at the start of the peak flow period (annual peak flow snowline). The vertical line indicates the date of onset of the peak flow period.

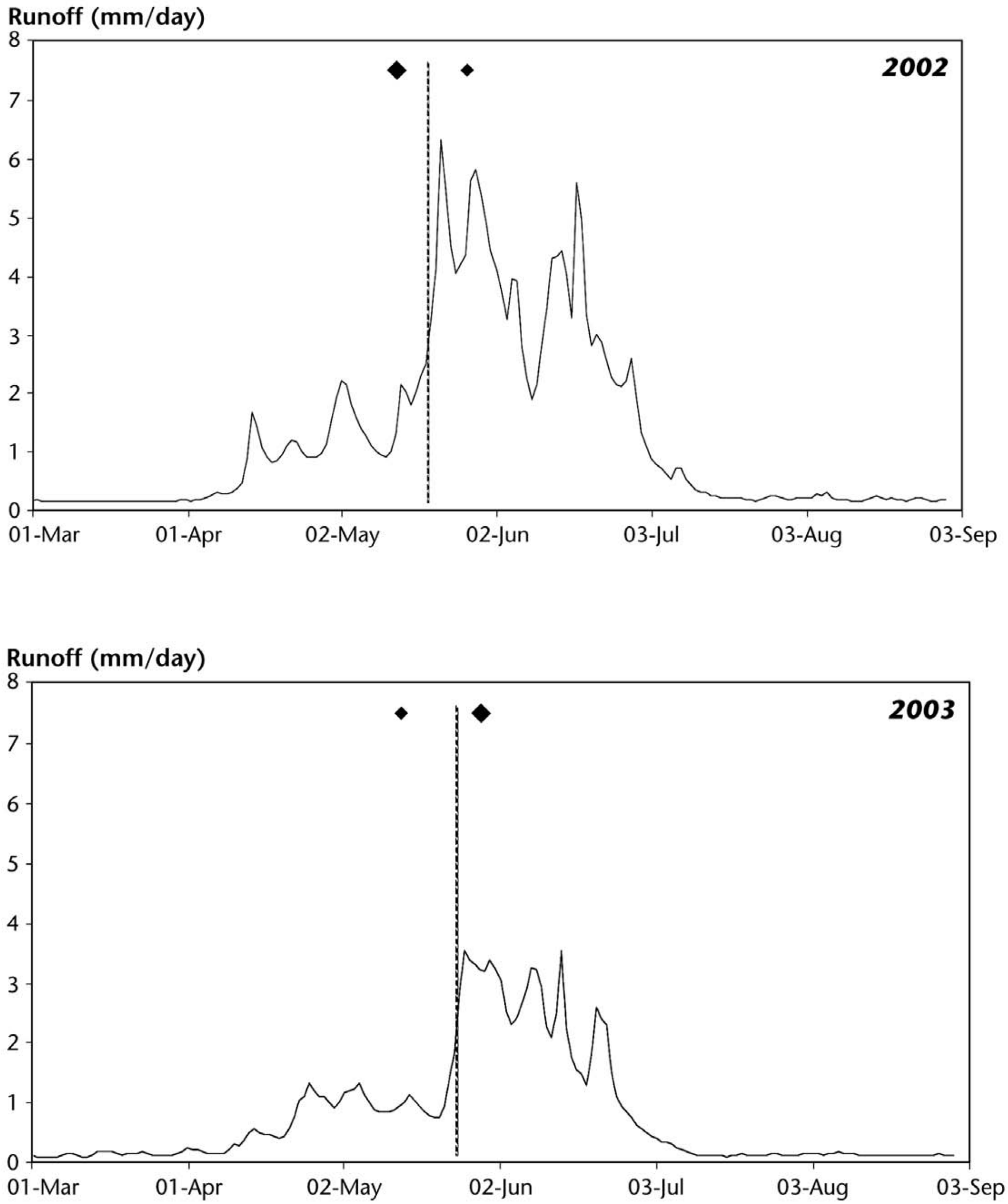

FIGURE 3B. Spring freshet hydrographs for 2002–2003 for Mission Creek near East Kelowna (WSC Station No. 08NM116) and snowline survey dates (diamond symbols). The large diamond indicates the snowline selected to represent conditions at the start of the peak flow period (annual peak flow snowline). The vertical line indicates the date of onset of the peak flow period.

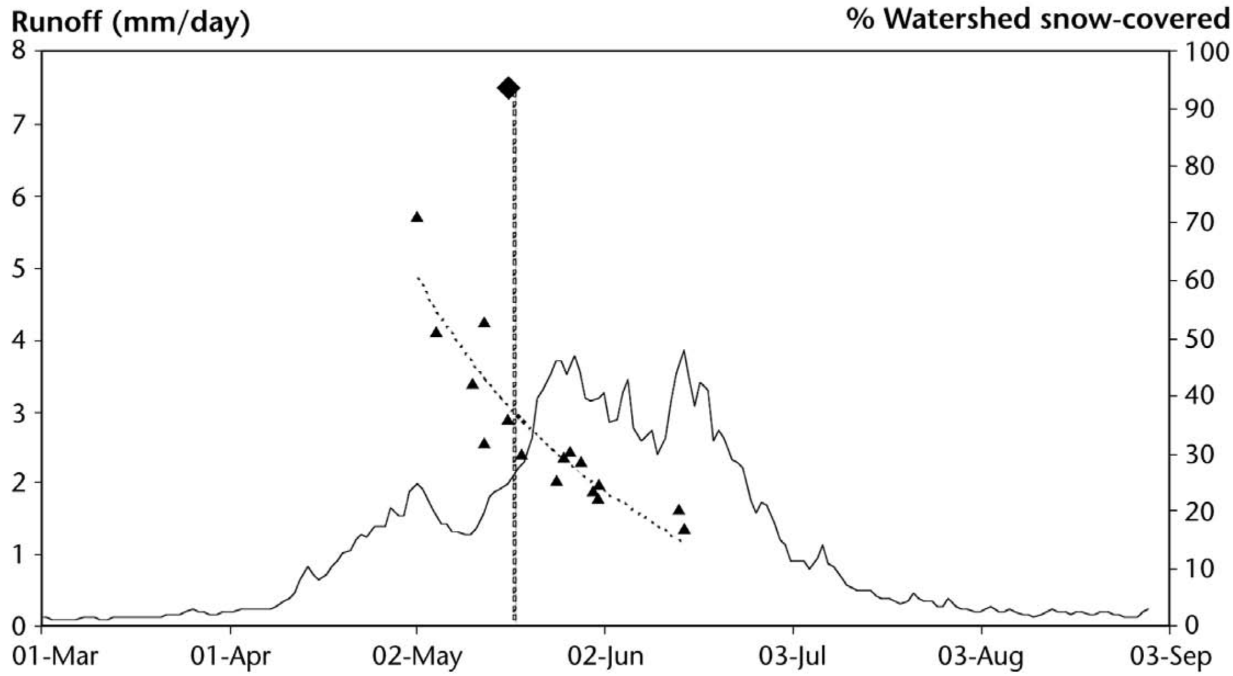

FIGURE 4. Portion of the watershed snow-covered during the snowline surveys (triangles) to which a snow depletion curve is fitted (dashed curve). Average runoff for 1999–2003 (solid line) with the average date of survey for the annual peak flow snowlines (diamond) and the average date of onset of the peak flow periods (vertical line).

Results

In total, four snowline surveys were conducted in 1999, five in 2000, three in 2001, and two in each of 2002 and 2003. The return intervals for the annual peak flows in these 5 years were 2.3, 2.7, 1.1, 3.9, and 1.0 years, respectively, based on 38 years of data. It is evident that the survey dates in 1999–2001 were adequate, but the surveys occurred too infrequently in both 2002 and 2003 (Figures 2, 3A, and 3B).

For 1999–2003, the average snow-covered area above the annual peak flow snowlines was 228 km^2, which represents 38% of the watershed (range between 29 and 53%; Method 1). The low frequency of surveys in 2002 and 2003 increased the range in results because the surveys that represented the 2002 and 2003 annual peak flow snowlines were approximately 1 week too early and 1 week too late, respectively. The average snow-covered area from the five annual peak flow snowlines represents the average at the onset of the peak flow periods, which is an indication of the average area of the snow-sensitive zone ignoring the time for water to flow from the source area to lower Mission Creek (i.e., time of concentration). This value suggests that an H38 represents the average lower extent of the snow-sensitive zone for the peak flow return intervals captured within the study period. However, it may be more important to consider the greatest snow coverage—53% spatial extent in 2002—as most conservative in representing the snow-sensitive zone (Table 1; Figure 5).

Figure 4 shows that the average survey date of the five annual peak flow snowlines coincides well with the average onset date of the peak flow periods. Based on the snow depletion curve (Figure 4), the average snow-covered portion of the watershed during the average onset date of the peak flow period is approximately 37% (Method 2). This value is generally consistent with the 38% determined by averaging the snow-covered areas based on the five annual peak flow snowlines (Method 1).

A map of the watershed boundary showing the H38, the H60, and the five annual peak flow snowlines is presented in Figure 5. The H38 generally coincides with the annual peak flow snowlines, although notable deviations occur in the Belgo Creek drainage resulting from influences on snow accumulation and melt processes that are more complicated than a simple elevation dependency. In contrast to the H38, the H60

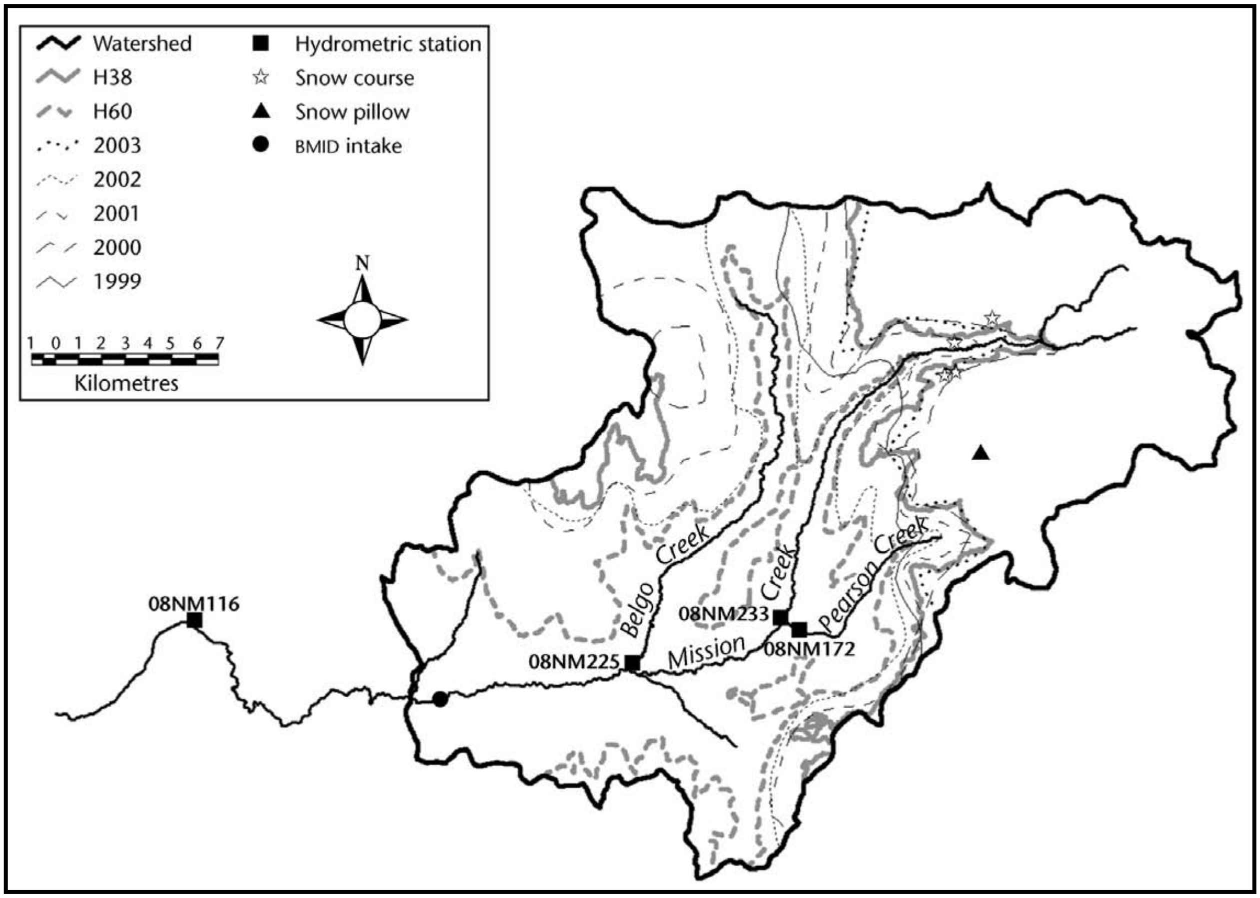

FIGURE 5. Watershed map indicating the locations of the H60, the H38, and the annual peak flow snowlines. The locations of the hydrometric stations, the snow pillow station, and four snow course sites are also indicated.

greatly misrepresents the annual peak flow snowlines and, consequently, also over-estimates the lower extent of the snow-sensitive zone.

The area-elevation curve for the watershed is presented in Figure 6 along with the positions of the H38, H60, and the five annual peak flow snowlines. The H38 corresponds to an elevation of 1520 m; the elevation of the H60 is 1300 m.

Discussion

Our results suggest that the H38 contour elevation is more applicable than the H60 for representing the average lower extent of the snow-sensitive zone in the Mission Creek watershed (Figure 5). However, it is important to consider several weaknesses in the analyses and results. Mainly, that snow accumulation and melt processes are complicated by numerous physical processes varying over space and time. This process variability caused the surveyed snowlines to vary from simple contour elevations and caused inter-annual variability in the locations of the annual peak flow snowlines. Furthermore, variation in survey frequency from year to year caused some annual peak flow snowlines to be more representative of conditions upon onset of the peak flow period compared to others (e.g., 2002 poorly represented).

The spatial distribution of winter snow accumulation and subsequent spring snowmelt is physically dependent on the distribution of meteorological conditions throughout winter and spring: primarily precipitation, incident solar radiation, long-wave radiation, and wind turbulence. These conditions are controlled by several factors ranging from a continental scale to a plot scale and includes global atmospheric circulation, regional and local topography, and vegetation cover. Meteorological conditions determine the magnitude and form (solid, liquid, or gas) of precipitation and

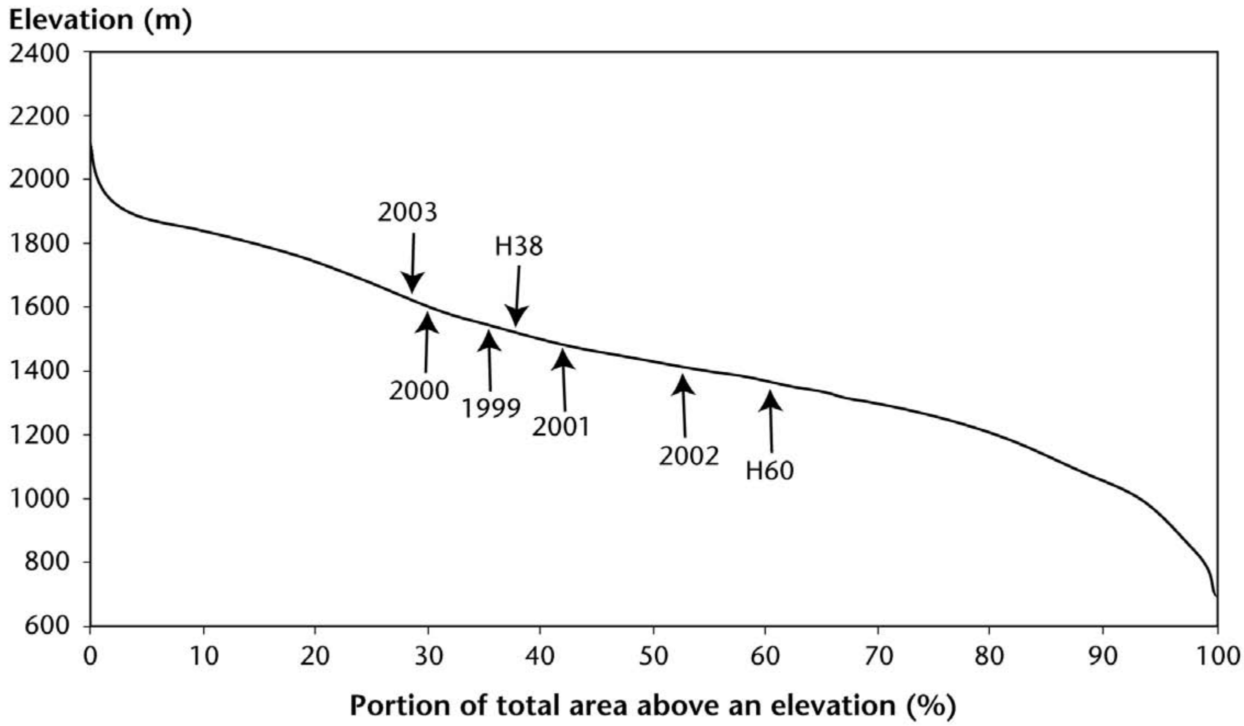

FIGURE 6. Area-elevation curve indicating the elevations of the H60, the H38, and the annual peak flow snowlines.

evaporation during the snow accumulation phase. During the snowmelt phase, meteorological conditions determine the magnitude and form of energy exchange between the snowpack, underlying soil, and atmosphere, and, thereby, govern the magnitude of snowmelt and evaporation.

With all of these factors controlling patterns of snow distribution, it is evident why the surveyed snowlines do not follow any specific contour elevations and why inter-annual variability in the annual peak flow snowlines occurs. Instead, the snowlines vary with elevation, aspect, slope gradient, and forest cover. For example, the snowlines are generally higher in elevation (relative to the H60 contour elevation) on south-facing and convex slopes compared to north-facing and concave slopes (Figure 5). Moreover, the rate of snowline retreat varies through space and time depending on the conditions of the snowpack (i.e., ripeness), the local physiography, and the near-term weather conditions. Therefore, the frequency of snowline surveys is an important consideration when inferring the validity of any one annual peak flow snowline and its representation of the conditions upon onset of the peak flow period.

All of the above complexities make it difficult to select one specific contour elevation to represent the snow-sensitive zone. Nevertheless, it is important to utilize more regionally specific data to improve watershed management approaches wherever possible rather than rely completely on direction from studies in regions of vastly different physiography. This study aimed to provide this local information, but the findings should be applied to watershed management with caution in light of the complex physical processes discussed above.

Figure 5 indicates that the H38 contour elevation is generally consistent with the annual peak flow snowlines through the upper Mission Creek and Pearson Creek drainages, although the 2002 snowline is consistently lower in elevation. In contrast, the H38 and the annual peak flow snowlines all deviate greatly through the Belgo Creek drainage, particularly to the west. Within the area west of Belgo Creek, the snow-covered areas during onset of the 2001 and 2002 peak flow periods were more than double the area above the H38, whereas the snow-covered area during onset of the 2000 peak flow period was approximately half the area above the H38 and snow was absent during onset of the 1999 and 2003 peak flow periods. Although the snow-covered area in 2002 (Figure 5) was greater in extent and generally lower in elevation than in all other years, inference

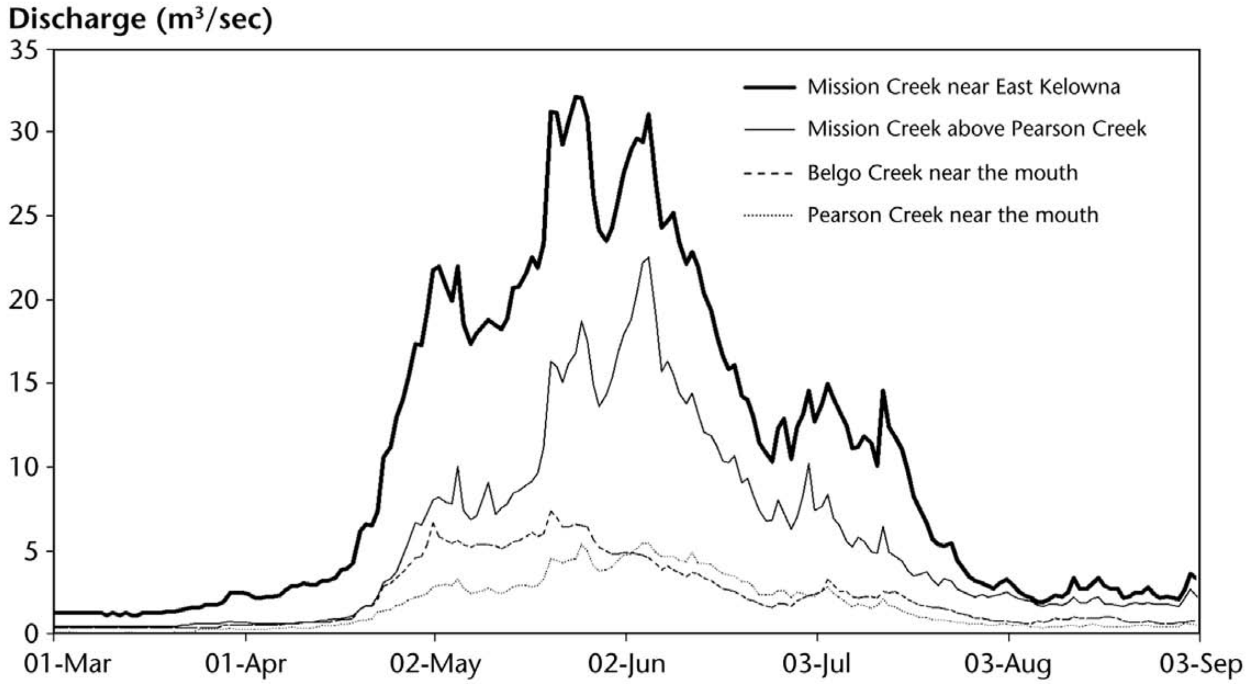

FIGURE 7. Average 1977–1982 spring freshet discharge for Mission Creek near East Kelowna (lower Mission Creek; WSC Station No. 08NM116) compared to that for Pearson Creek near the mouth (WSC Station No. 08NM172), Belgo Creek near the mouth (WSC Station No. 08NM225), and Mission Creek above Pearson Creek (upper Mission Creek; WSC Station No. 08NM233).

regarding an appropriate snow-sensitive zone should consider that the 2002 annual peak flow snowline was surveyed approximately 1 week before the onset of the peak flow period (Figure 3B); the subsequent survey in 2002 (approximately 1 week after the onset of the peak flow period) found almost no snow west of Belgo Creek with only 31% of the watershed snow-covered. Hence, inference from these results is limited by the relative infrequency of survey dates in 2002.

For the period of 1977–1982 (the only period of overlapping hydrometric data), hydrometric data for Pearson Creek near the mouth, Belgo Creek near the mouth, and Mission Creek above Pearson Creek (upper Mission Creek) was compared with Mission Creek near East Kelowna (lower Mission Creek). The comparison suggests that Belgo Creek generally decreases in discharge throughout the Mission Creek peak flow period (Figure 7). Belgo Creek generates high flows primarily during the early spring freshet period (rising limb of the Mission Creek hydrograph) and is in recession while upper Mission Creek and Pearson Creek are generating high flows at lower Mission Creek during the later spring freshet period (Figure 7). The data also show that upper Mission Creek is clearly dominant in generating flows at lower Mission Creek throughout the spring freshet, particularly during the peak flow period. Analyses of intra-annual discharge data for 1977–1982 also support these findings. These results minimize concerns regarding inconsistency between the H38 and the annual peak flow snowlines in the Belgo Creek drainage. These results also support using the H38 contour elevation to represent the average lower extent of the snow-sensitive zone for the Mission Creek watershed since the H38 and the annual peak flow snowlines are generally consistent in location through the upper Mission Creek and Pearson Creek portions of the watershed. In contrast, the area above the H60 incorporates a large portion of the Belgo Creek drainage—an area that has limited influence on Mission Creek discharge during the peak flow period.

Runoff from the upper 38% of the watershed is most important for generating peak flows for the return intervals captured in this study. Based on this, the upper 38% of the watershed is most sensitive to forest harvesting in terms of potential impacts on peak flows. A conservative approach would be to determine the snow-sensitive zone based on the annual peak flow snowline that encompasses the largest upslope area.

This would suggest using an H53 based on the 2002 survey; however, as discussed above, the 2002 data are problematic due to infrequent surveys. Ignoring the 2002 data, the 2001 results would suggest using an H42—a value similar to the average value of H38. The difference between H42 and H38 is likely within the range of accuracy of the snowline mapping process.

Accepting a final contour elevation of H38 to represent the average lower extent of the snow-sensitive zone suggests that the snow-sensitive zone makes up a much smaller portion of the Mission Creek watershed than in the alpine/subalpine watersheds of the Nelson region (Gluns 2001; Whitaker *et al.* 2002; Schnorbus and Alila 2004). However, the upper extent of the snow-sensitive zone was not determined in this study or in any of the Nelson studies. To do so, it is necessary to gather spatially and temporally distributed SWE data at a range of elevations above the mapped snowlines to interpolate the upper extent of melting snow throughout the peak flow period. The data of greatest importance would be the upper extent of SWE loss on the last day of the peak flow period. Locations above this upper melt line would not contribute to runoff during the peak flow period. Perhaps even the uppermost elevations in the Mission Creek watershed would experience SWE loss during the peak flow period and, therefore, would be part of the snow-sensitive zone; however, this has not been confirmed and needs further study.

Snow course data were gathered at four sites. Snow pillow data were available from one site in the Mission Creek watershed throughout the 1999–2003 spring freshets (Figure 5); however, the snow courses and the snow pillow range between 1400 and 1780 m. As the watershed is 2222 m at its highest point, the available SWE data are not sufficient to infer the upper extent of the snow-sensitive zone. Since it is uncertain whether contributions to streamflow (in the Mission Creek and Nelson watersheds) are derived from all snow-covered areas during the peak flow period (i.e., the highest elevations in the watershed may not undergo snowmelt until well after the peak flow period), the actual percentage of watershed area contributing to the peak flow period may be similar between the Mission Creek and the Nelson watersheds. This is supported by the modelled results, which show the area in the Redfish Creek watershed where forest harvesting is likely to change peak flows is between the H80 and the H40, equalling 40% of the watershed area (Whitaker *et al.* 2002). This value is generally consistent with the 38% of the Mission Creek watershed contained within the snow-sensitive zone, as determined in this study.

The reasons for greater relative contribution to peak flows from lower elevations in the Nelson watersheds compared to lower elevations in the Mission Creek watershed include the factors that control the spatial dynamics of snowmelt inputs coupled with those controlling hydrologic connectivity between meltwater source areas and the stream network. In short, the primary reasons for the greater contributions are likely related to greater snowpack conditions, particularly at lower elevations, and higher forest densities at lower elevations in the Nelson region. In the Okanagan region, low precipitation and generally mild temperatures throughout late winter frequently result in transient snowpack conditions throughout the lower portion of the Mission Creek watershed—areas that are generally comprised of grassland and open-canopy forest. This leaves snowmelt in the middle portion of the watershed to generate early spring freshet runoff and snowmelt in the upper portion to generate runoff throughout the middle and late spring freshet. Since SWE generally increases with large-scale rises in elevation, and climatic conditions in late spring facilitate greater snowmelt rates compared to early spring, the peak flow is expected to occur while the upper portion of the watershed is generating runoff. Generally, the hydrologic processes that control runoff source area patterns are complex and beyond the scope of this study.

Several additional limitations should be considered in applying the results of this study. First, the greatest peak flow return interval for the 5 years of snowline surveys was about 4 years in 2002. It is uncertain whether snowline patterns during years with extreme peak flows (> 10 years) would deviate significantly from those presented here. The current results should be applied with caution until such data are gathered and added to the current analysis. Second, understanding the spatial extent of snow cover is only one important factor. Runoff generation mechanisms in snowmelt-dominated systems are not well understood. In particular, spatial patterns of snowmelt and hydrologic connectivity between meltwater input areas and the stream network have not been well studied. The influence on runoff from areas immediately downslope from the snowline and, thus, most recently snow-free, is uncertain. Third, the average time for water to flow from meltwater source areas to lower Mission Creek is unknown, but is relevant in understanding the timing of source area contributions to flow dynamics. Because of these uncertainties regarding runoff processes, the findings of this study should be applied conservatively. All of these topics need further study.

Management Implications

The data presented in this research report help to clarify potential sources for water supply and the associated snow-sensitive zone in the Mission Creek watershed, but additional process-based investigation of the spatial dynamics of streamflow generation is greatly needed for further clarity. In the past, 60% (360 km^2) of the watershed was considered sensitive to forest harvesting impacts on peak flows. Our data analysis shows that approximately 38% (228 km^2) of the watershed is considered sensitive. Consequently, an area of 132 km^2 that was once included in the hydrologically sensitive land base can now be more easily managed for other priorities—environmental, social, or economic. This gives watershed managers greater certainty regarding the area in need of careful management for water supply purposes. Forest managers can minimize, to a greater extent, the potential effects of development on water supply by reallocating timber supply from areas considered sensitive for peak flow purposes to areas considered less sensitive.

Watershed management decision making should, however, be tempered by the need to study in greater detail the spatially distributed effects of clearcutting on synchronization and desynchronization of runoff. Since canopy removal increases snow accumulation and snowmelt rates, and advances snowmelt timing (Troendle and King 1985; Cheng 1989; Marks *et al.* 1998; Storck *et al.* 1999; Troendle *et al.* 2001; Schnorbus and Alila 2004; Winkler *et al.* 2005), it can be inferred that harvesting in the snow-sensitive zone could synchronize mid- and late-freshet runoff with early freshet runoff and advance the timing of the peak flow period. In contrast, harvesting below the snow-sensitive zone could advance the timing of early freshet runoff and result in an earlier start to the spring freshet with a more gradual rising limb. Likewise, slope aspect greatly influences the timing of snowmelt and needs further study.

Snowline studies are an important tool that can be used by hydrologists and forest planners to better define the spatial extent of snow cover and the portions of a watershed that contribute the greatest to peak flows. In this study, the snowline surveys not only improved our understanding of the watershed areas most sensitive to forest harvesting, but also provided insight into the relationship between the spatial distribution of snowmelt and the watershed physiography associated with annual peak flow events.

The H38 is more appropriate than the H60 in reasonably representing the snow-sensitive zone of the Mission Creek watershed for the peak flow return intervals captured within the study period.

Conclusions

This study shows that the H60 concept does not reasonably represent the snow-sensitive zone of the Mission Creek watershed for the peak flow return intervals captured within the study period. Rather, the H38 is more appropriate. Based on these findings, the upper 38% of the watershed is considered most sensitive to forest harvesting in terms of potential impacts on peak flows. Managing water resources using the H38 at 1520 m compared to using the H60 at 1300 m means that an area of 132 km^2 can be more easily managed for other priorities. Upper Mission Creek is clearly dominant in generating flows at lower Mission Creek throughout the entire spring freshet; Belgo Creek is in recession during the peak flow period. Watershed managers now have greater certainty regarding the area in need of careful management for water supply purposes. This may be important in the assessment of potential forest harvesting impacts in the watershed.

Application of our findings to other regional watersheds should be done with caution because of the complex nature of snowmelt runoff processes. Particular attention should be given to ensuring similar watershed physiography, elevation range, and climatic conditions. Ideally, snowline survey data should be gathered for other watersheds to confirm consistency with the Mission Creek findings. The surveys should be conducted at least weekly throughout the spring freshet period to distinguish actual inter-annual variability from error associated with the frequency of surveys.

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Test Your Knowledge . . .

Snow cover extent during spring snowmelt in the south-central interior of British Columbia

How well can you recall some of the main messages in the preceding Research Report?
Test your knowledge by answering the following questions. Answers are at the bottom of the page.

1. Spatial variability of the snowline is influenced strongly by what factors?
   A) Elevation and slope gradient
   B) Elevation and aspect
   C) Aspect and forest cover
   D) All of the above

2. The snow-sensitive zone is the portion of the watershed that generates the peak flows.
   A) True
   B) False

3. What period(s) of streamflow is/are important for influencing stream stability?
   A) Only the peak flow
   B) All periods of sustained high flow
   C) Only the period of rising flow before the peak flow
   D) Only the period of low flow

Answers

1. D 2. A 3. B