Regional Hydrology

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INTRODUCTION

Stream water is a valuable resource. It is withdrawn for irrigation in many parts of British Columbia, and is commonly the dominant source for drinking water. Aquatic ecosystems also depend on streamflow, since the timing, magnitude, and temperature of the flows determine the health of the aquatic ecosystem. The current decline of the populations of some indicator and economically important species, such as coho salmon, highlights the importance of streamflow conditions. The water carried by the streams may also pose a significant hazard. Peak flows can destroy stream crossings and other instream engineered structures, erode land adjacent to the stream, and flood the surrounding areas.

The flow carried by a stream varies over a range of time scales. Over short time scales (e.g., less than a day to a few days), it is controlled by the passage of weather events and their influence on rainfall, snow and ice melt, and evapotranspiration. Over longer time scales (years to decades), larger-scale climatic processes such as El Niño play an important role. However, streamflow tends to exhibit typical seasonal patterns, or regimes, which can be broadly classified in relation to the dominant sources of streamflow: rainfall, snowmelt, and glacier melt. Understanding the variability of regimes both within and among regions is an important first step in assessing the state and potential sensitivity of a watershed to land use practices. For example, forest harvesting has different influences in rain- and snow-dominated watersheds. For this reason, the *Forest Practices Code of British Columbia Act* imposed different watershed assessment procedures for coastal and interior regions of British Columbia.

This chapter explores the typical spatial variations in the seasonal flow regimes, providing generalized explanations for the observed patterns. It also explores the magnitude, timing, and processes producing peak flows across British Columbia. Practitioners should be able to use this chapter to characterize the seasonal flow regimes and peak flow regimes for ungauged drainage basins across British Columbia. Furthermore, the analysis that we present can act as a template for subsequent analysis of basins that are gauged, and also provide a context for interpreting the results of such an analysis.

Rain-dominated regimes are found primarily in coastal lowland areas and at lower elevations of the windward side of the Coast Mountains. In these regimes, the temporal variability of streamflow closely follows that of rainfall, though smoothed somewhat by the effects of water storage and movement in soils, groundwater, lakes, and wetlands. As a result, these regimes typically exhibit the highest monthly discharge values in November and December, since this is when the most intense frontal weather systems move over the British Columbia coast (Figure 4.1, Carnation Creek). The lowest monthly flows occur in July and August, when a blocking high-pressure system typically directs precipitation-generating weather systems away from at least the southern half of the province.

Snowmelt-dominated (or nival) regimes occur in the interior plateau and mountain regions, and in higher-elevation zones of the Coast Mountains. In these zones, winter precipitation dominantly falls as snow and remains in storage until spring melt. As a result, these regimes exhibit low flows through winter, and high flows in May, June, and July (Figure 4.1, Fishtrap and Redfish Creeks). Low flows may also occur during the late summer and fall as a result of low precipitation inputs and the exhaustion of the snowpack water supply. The regime for Coquihalla River is mostly nival, but the drainage basin has sufficient low-elevation area and proximity to maritime influences that it has a stronger influence of autumn rains than Fishtrap and Redfish Creeks.

Many basins, especially in coastal and near-coastal regions of British Columbia, exhibit characteristics of both rain- and melt-dominated streamflow regimes. These are referred to as mixed-regime or hybrid-regime basins. For example, Capilano River has rain-dominated high flows from October to January that are of a similar magnitude to the melt-dominated flows in April to June (Figure 4.1). For mixed-regime basins, the relative importance of the rainfall influence decreases inland from the coast or northwards up the coast; in both cases, the mean temperature tends to decrease, promoting the occurrence of snow rather than rain during the winter. The relative importance of the rain regime also decreases with increasing mean basin elevation for the same reason. Even on the coast, winter temperatures are low enough that a significant proportion of the precipitation will fall as snow at elevations greater than about 1000 m above sea level (asl).

A distinct population of mixed-regime basins also occurs in the northeastern part of the province, where snowmelt produces a peak in early May owing to the relatively low relief in the area. In the northeast, precipitation peaks in the summer months as a result of convective precipitation (see Chapter 3, "Weather and Climate"). This produces an increase in the seasonal runoff in June and July, which has the appearance of a snowmelt-dominated regime, but is the product of snowmelt combined with rain-related runoff.

Drainage basins with more than two to five percent of the area covered by glaciers have regimes similar to nival regimes, except that the period of high flows extends from about May to August or September, and low-flow conditions occur only when precipitation is accumulating in the snowpack, usually from December to March (Figure 4.1, Lillooet River). The extended melt freshet is partly associated with the higher elevations typical of glacierized drainage basins (i.e., basins that currently have glaciers covering more than two to five percent of the watershed) that hold snow later into the summer, but is primarily associated with the presence of glaciers which, during the melt season, act as inexhaustible reservoirs of water.

Although streamflow regimes are dominantly controlled by seasonal patterns of temperature and precipitation over a drainage basin, a range of watershed characteristics also influence the temporal distribution of streamflow. For example, drainage basins on the interior plateaus tend to have low relief, and have a snowmelt period that is synchronized over most of the basin, resulting in a shorter spring freshet period. Mountainous drainage basins, in contrast, typically have an extended freshet caused by the sequential melting of snow from lower to higher elevation bands. This contrast is illustrated in Figure 4.1 by the regimes for Fishtrap Creek (plateau) and Coquihalla River and Redfish Creek (mountain drainages). Presence of lakes, ponds, and wetlands can attenuate flows, decreasing high flows as water goes into storage and augmenting low flows through storage depletion. The role of geology, through its influence on groundwater storage and discharge, can be particularly important. For example, a drainage

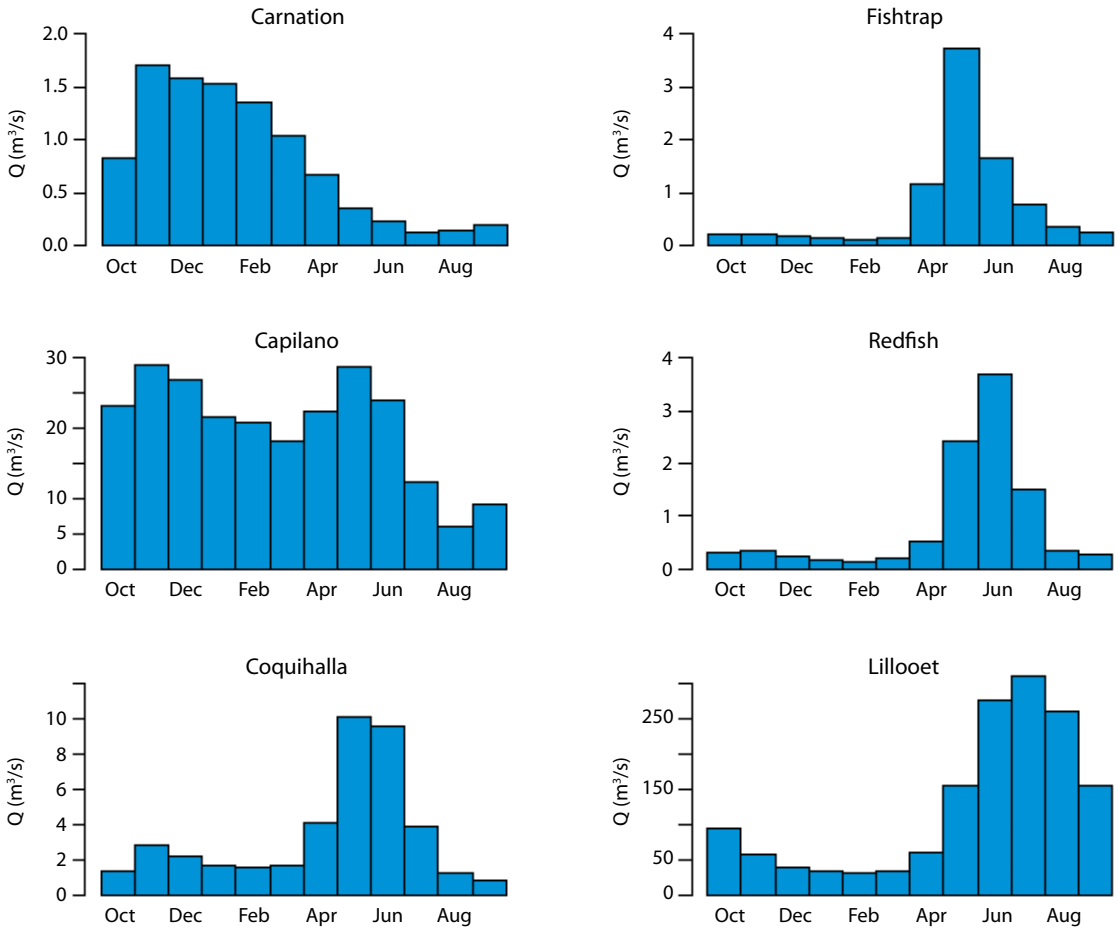

FIGURE 4.1 *Examples of long-term average streamflow regimes drawn from southern British Columbia. Values are monthly average discharge (Q) in m³/s.*

basin underlain by highly permeable bedrock will tend to have more water recharging the groundwater during rain and melt events, thus decreasing storm runoff but moderating flow during dry weather. Basins underlain by relatively impermeable bedrock such as granite will tend to have less groundwater influence on the stream hydrograph; however, even for relatively impermeable bedrock, flow through fracture systems can be important, particularly for smaller, headwater streams (Whyte 2004).

Glaciation has left a significant legacy in the hydrogeomorphic form and function of British Columbia watersheds (Brardinoni and Hassan 2006), especially the U-shaped valleys with oversteepened side slopes, as well as the surficial materials left behind as glaciers retreated. For example, many glaciated areas have shallow soils underlain by compacted till, which is relatively impermeable and promotes runoff generation as shallow saturated subsurface flow (Hutchinson and Moore 2000).

Streamflow regimes within a region may also depend on drainage basin scale, particularly in areas with high relief. Smaller basins, particularly those less than a few square kilometres in area, will tend to have higher mean elevations than larger drainage basins, leading to a stronger nival influence in regions with mixed streamflow regimes, and a delayed seasonal melt freshet in regions dominated by nival regimes.

The hydrographs in Figure 4.1 represent averages over a number of years; however, streamflow regimes can vary significantly in both the intra-annual pattern and overall magnitude of streamflow. Rain-dominated streamflow regimes closely reflect the input of precipitation to a drainage basin with relatively little smoothing or lagging associated with long-term storage within the basin. As a result, year-to-year variation in the seasonal distribution of the mean monthly discharge is significant, reflecting the sequence and intensity of the weather systems that affect a drainage basin in a given year (Figure 4.2). The monthly discharge pattern for a given year is therefore unlikely to closely resemble the average pattern for a number of years.

Snowmelt-dominated systems integrate precipitation inputs over the winter and spring within the snowpack, and then release the stored water during the spring-summer melt period. Consequently, the monthly discharge pattern for a given year is generally similar in shape, if not magnitude, to the long-term mean monthly discharge pattern (Figures 4.3 and 4.4).

For mixed-regime rivers, the relative strengths of the rain and snowmelt influences on the annual hydrograph vary from year to year, primarily depending on air temperatures during winter storms. For storms that are associated with relatively high air temperatures—for example, during El Niño years or the Pacific Decadal Oscillation (PDO) warm phase—

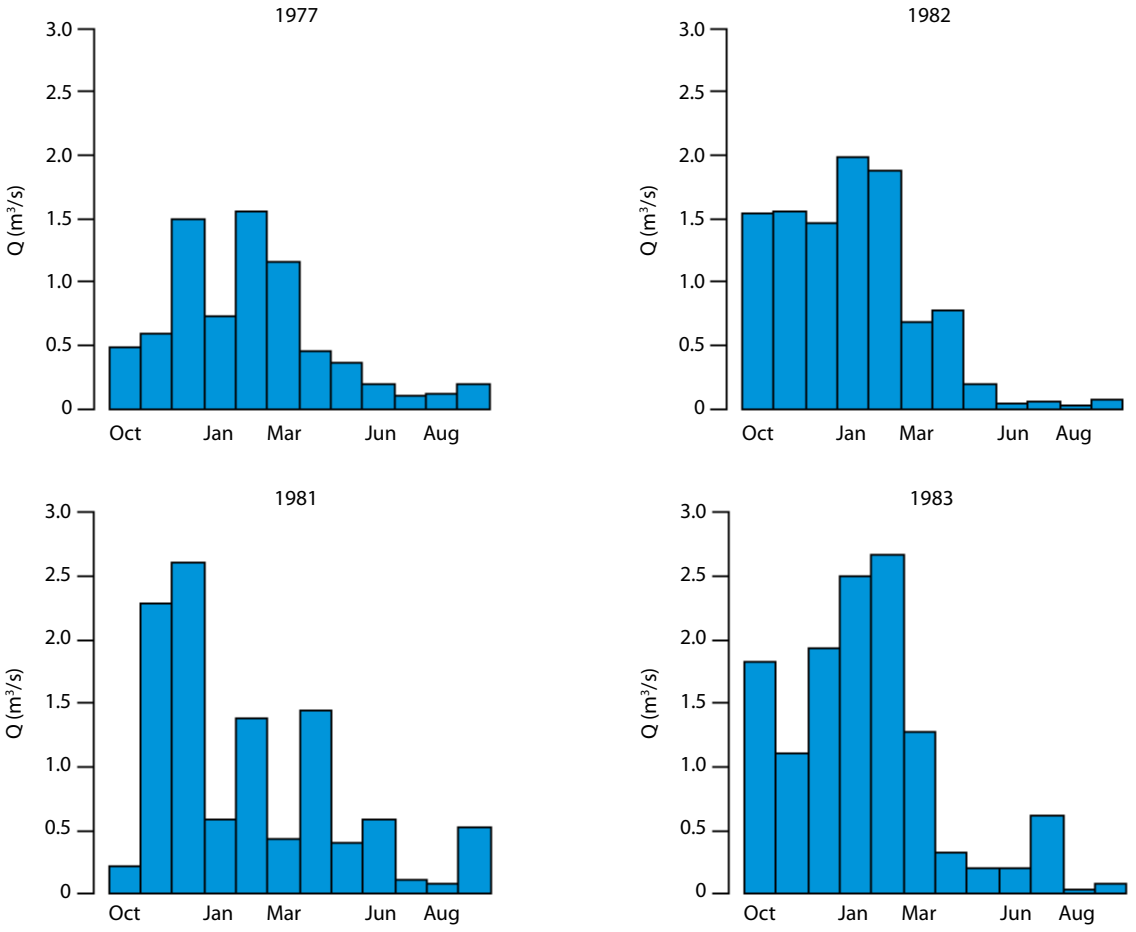

FIGURE 4.2 *Mean monthly discharge (Q) for Carnation Creek in 1977, and 1981–1983. Over southern British Columbia, 1977 and 1981 had generally warm, dry winters; 1982 had a cool, wet winter; and 1983 had a warm, wet winter.*

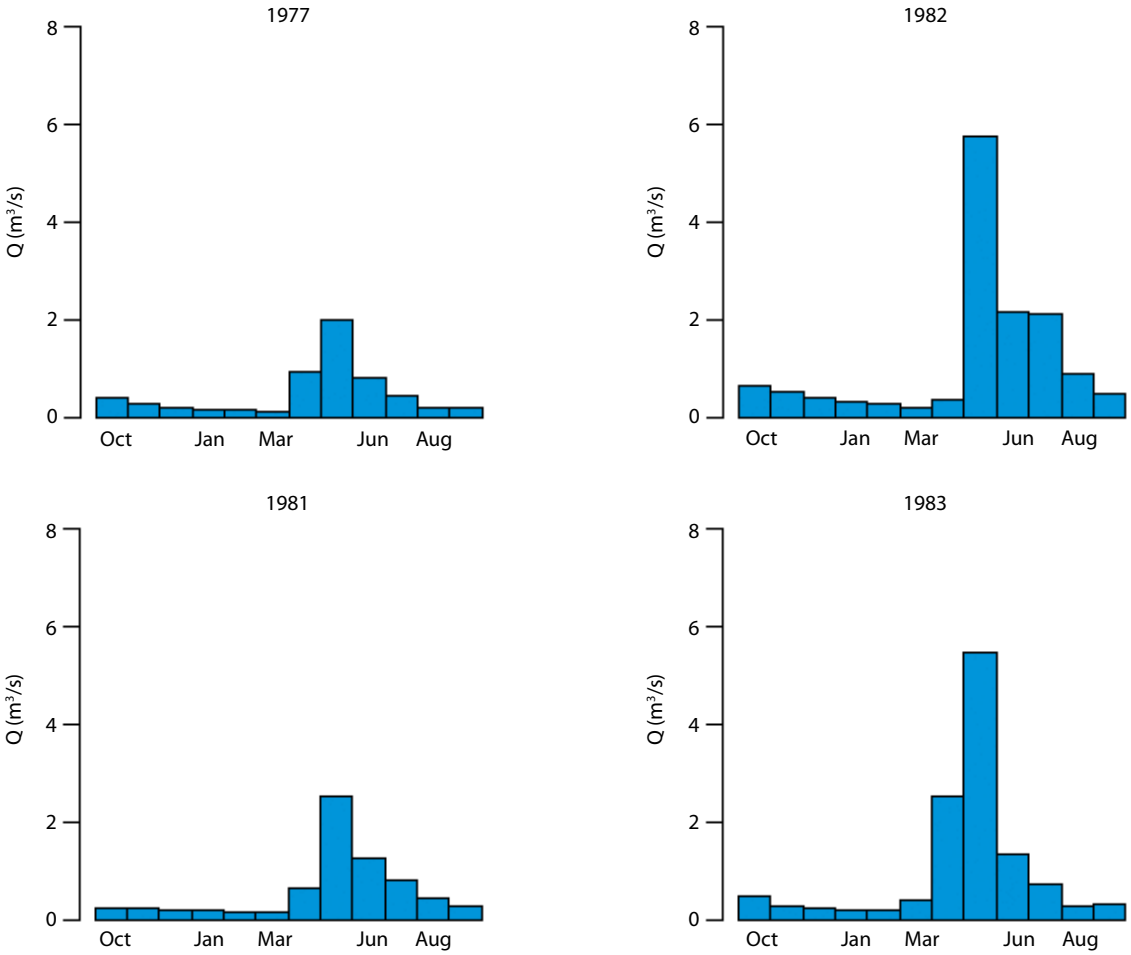

FIGURE 4.3 *Mean monthly discharge (Q) for Fishtrap Creek in 1977, and 1981–1983.*

precipitation falls mainly as rain. Conversely, in years dominated by cold storm systems (e.g., during La Niña years or PDO cold phase), more precipitation falls as snow and contributes to higher flows during the spring melt period. For example, Capilano River spring flows were relatively high during 1982, following a relatively cool winter that produced a deep snowpack (Figure 4.5).

In 1983, relatively warm winter conditions caused high rainfall and mid-winter snowmelt, producing high mid-winter streamflow. Coquihalla River also exhibits temperature-related responses. The relatively cool winter of 1982 produced an almost purely nival hydrograph, whereas the relatively warm winters of 1977 and 1981 produced stronger rainfall contributions (Figure 4.6). Like snowmelt-dominated streams, glacier-fed streams have relatively stable flow regimes (Figure 4.7). These regimes may be even more stable than purely nival regimes because glaciers effectively regulate the between-year variability in meltwater runoff by maintaining a source of meltwater after the seasonal snowpack has disappeared (Moore 1992; Moore and Demuth 2001).

In a year with low snow accumulation, snow will tend to melt off a glacier earlier in the season, exposing the less reflective glacier ice, which melts at a higher rate than snow exposed to the same meteorological conditions. Thus, the warm and dry conditions that produce relatively low summer streamflow from glacier-free portions of a basin increase meltwater runoff from glaciers and, in turn, increase streamflow (Stahl and Moore 2006). Conversely, the streamflow regimes for glacierized basins may vary over longer time frames as the glaciers in the basin advance or retreat in response to climatic variations and change. Even if climate remains relatively stable

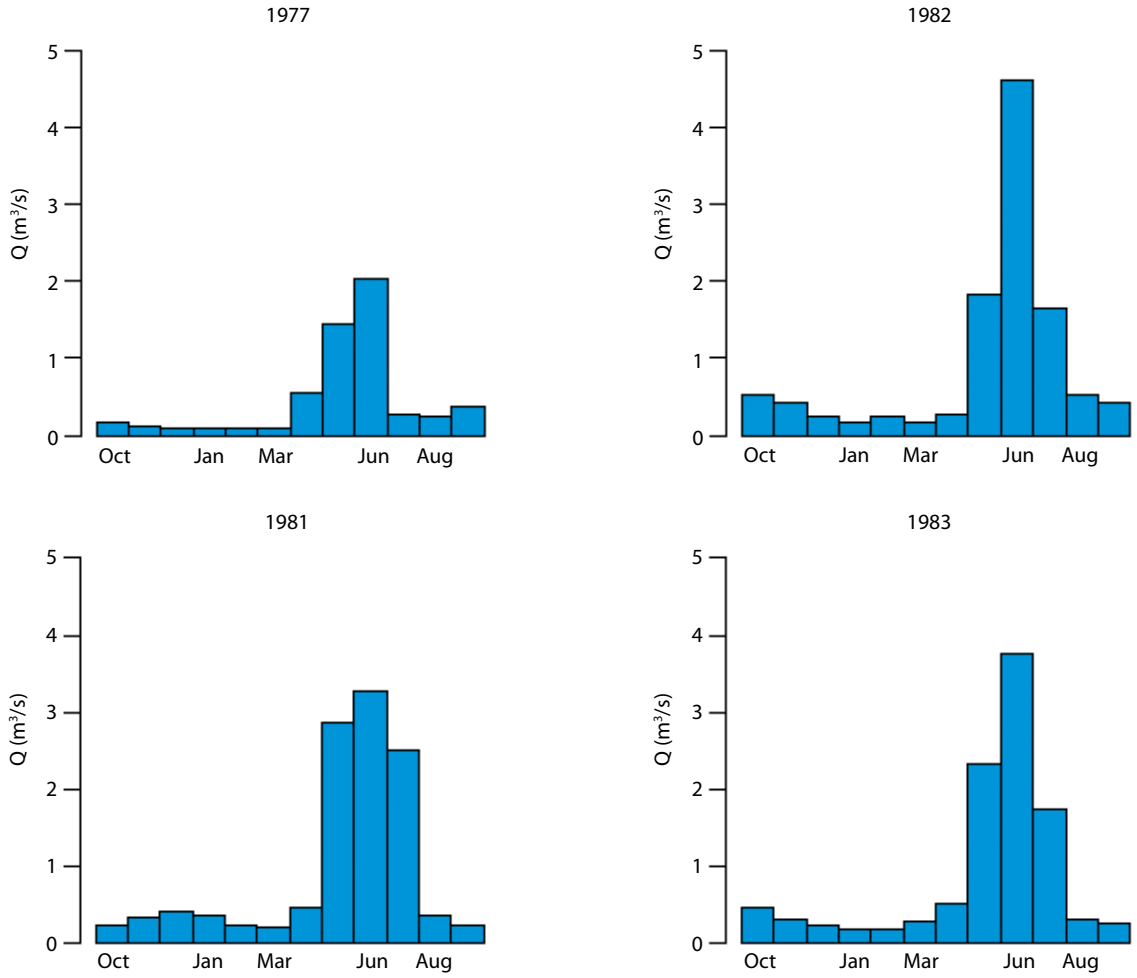

FIGURE 4.4 *Mean monthly discharge (Q) for Redfish Creek in 1977, and 1981–1983.*

within the period of interest, the streamflow regime may shift systematically due to the lag times in the response of the glaciers to climatic fluctuations.

Streamflow can also vary on decadal time scales in response to climatic fluctuations such as the PDO. For example, Moore (1996) showed that summer streamflow in the Capilano River displayed apparent step-shifts in the mean that were consistent with the timing of the PDO shifts. The lower winter temperatures associated with PDO cool phases result in more snow than rain. This augments snowmelt inputs and produces higher summer streamflow. Fleming et al. (2007) showed that streams with hybrid regimes were particularly sensitive to the effects of large-scale climatic variations such as the PDO and El Niño–Southern Oscillation (ENSO). In contrast,

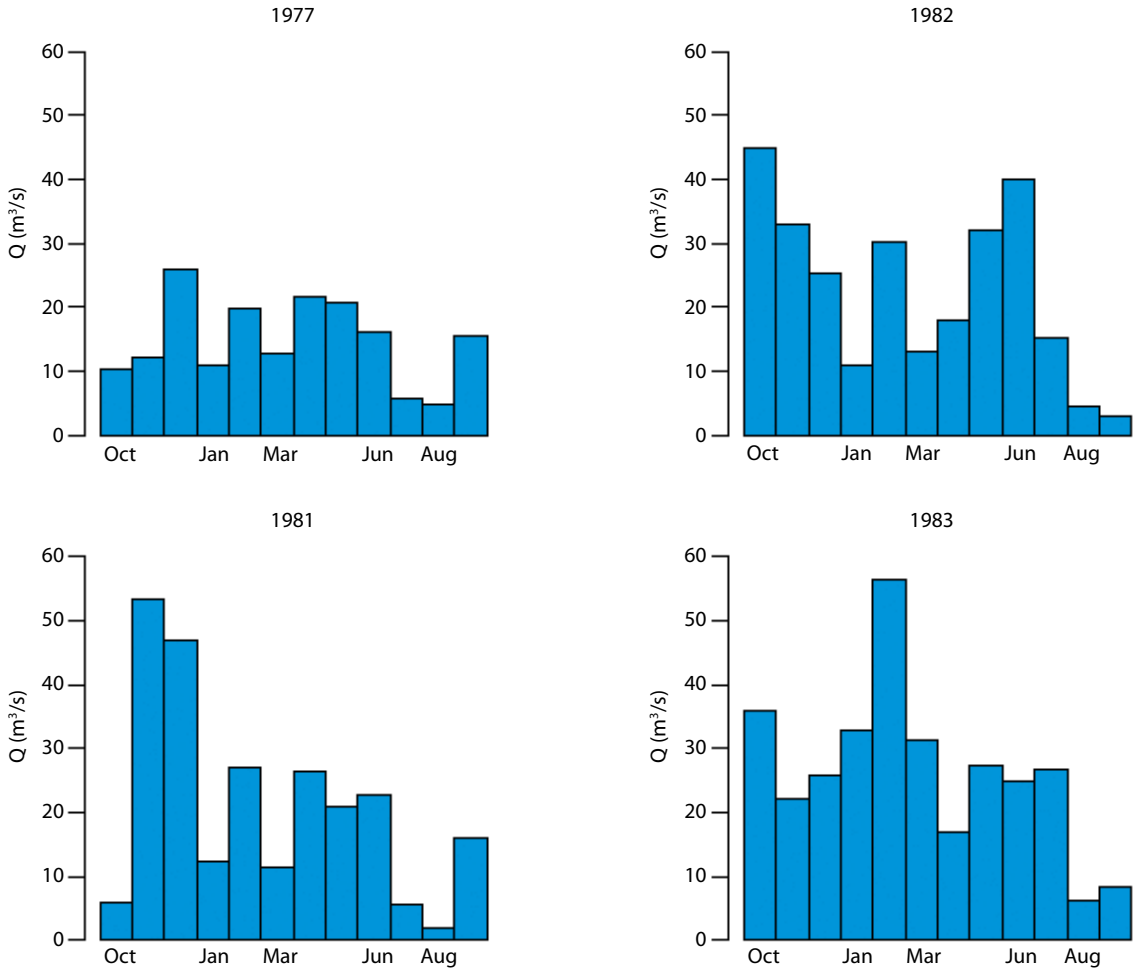

FIGURE 4.5 *Mean monthly discharge (Q) for Capilano River in 1977, and 1981–1983.*

glacier-fed streams, such as Lillooet River, appeared less sensitive to these influences.

Unfortunately, few rivers in British Columbia have records that capture all four phases of the PDO over the last century, limiting our ability to investigate geographic variability in response. Moore (1991), however, examined flow changes within the Fraser River drainage basin associated with the 1976–1977 shift, and found that the post-shift flows had decreased by about 20% on average, consistent with a coincident decrease in snow accumulation over southern British Columbia (Moore and McKendry 1996). Therefore, the PDO influences hydroclimatic patterns over at least the southern half of the province.

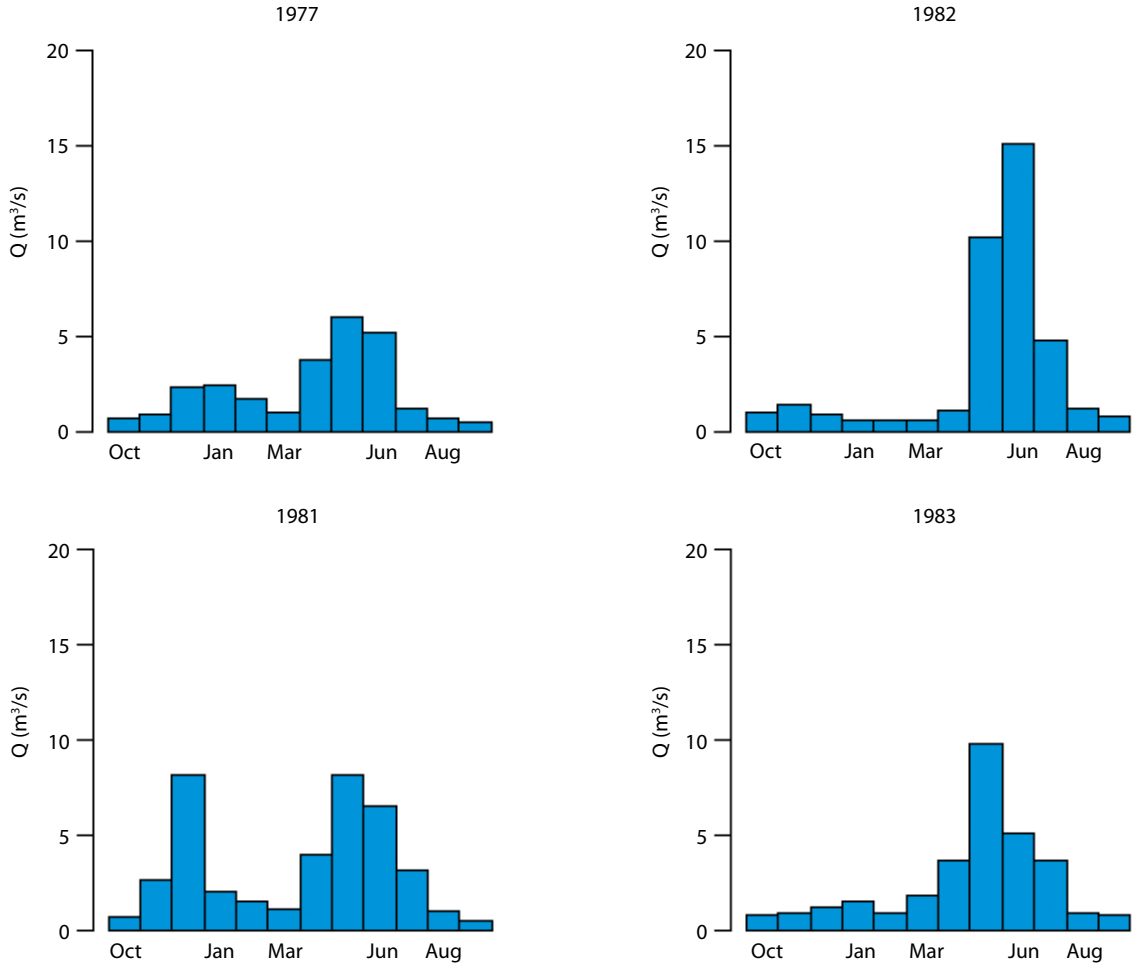

FIGURE 4.6 *Mean monthly discharge (Q) for Coquihalla River in 1977, and 1981–1983.*

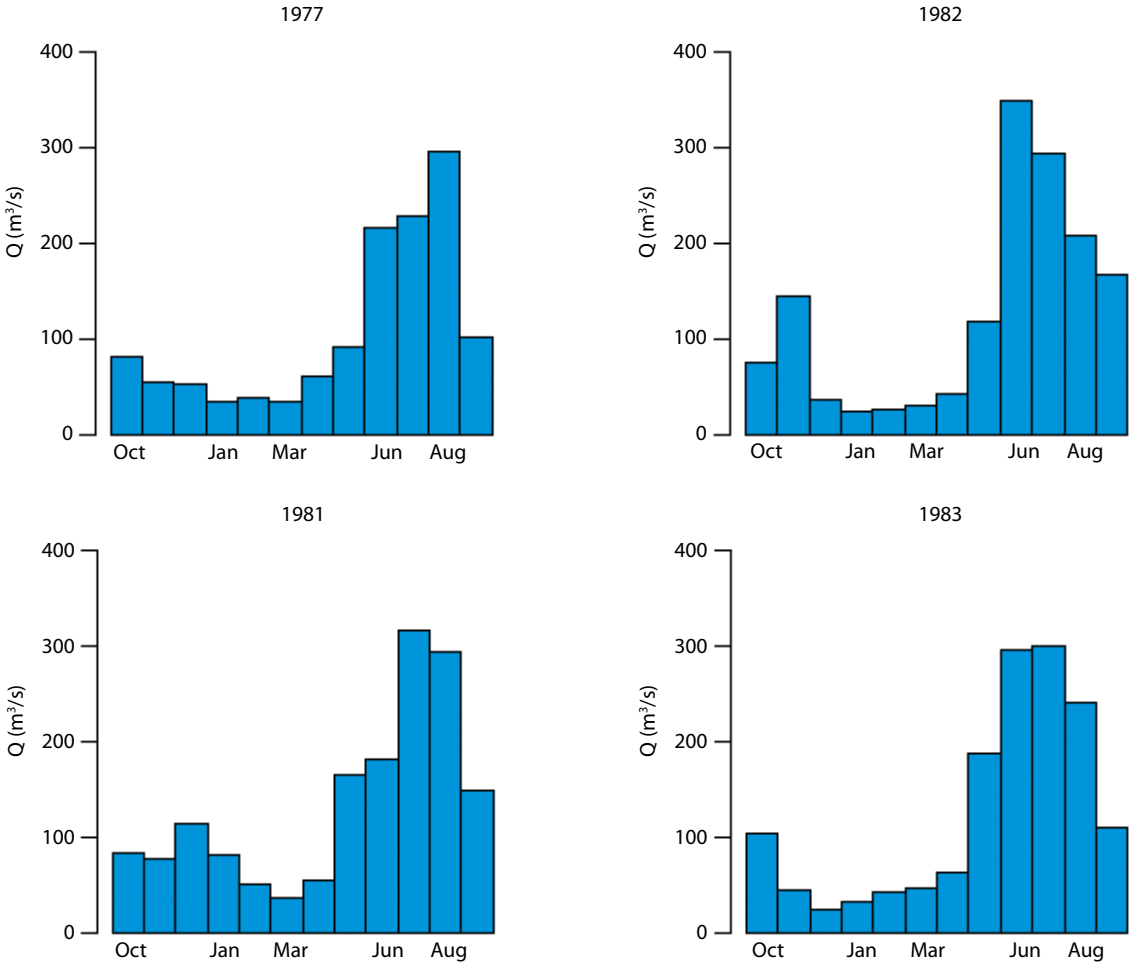

FIGURE 4.7 *Mean monthly discharge (Q) for Lillooet River in 1977, and 1981–1983.*

Seasonal streamflow regimes vary systematically across the province in conjunction with climate and physiography. Although coastal British Columbia exhibits various seasonal flow regimes as a result of the mixed streamflow-generating mechanisms, most of the Interior is characterized by snowmelt regimes that have similar streamflow patterns. The key differences between different regions of the Interior are: (1) the volume of streamflow per unit area, and (2) the between-month and between-year variability of the flow regime. In this section, the patterns are illustrated using mean monthly flow data for selected stations having similar drainage basin areas, organized into three west-to-east transects across the province (Figure 4.8; Table 4.1).

FIGURE 4.8 *Hydrometric stations in British Columbia used to illustrate the general spatial variations in monthly and peak flow characteristics. (Original map data provided by The Atlas of Canada http://atlas.gc.ca/ © 2007)*

TABLE 4.1 *Water Survey of Canada gauging sites related to each transect in Figure 4.8*

Station number	Station name	Latitude	Longitude	Drainage area above gauge (km²)	Mean basin elevation (m)	Period of record examined
Southern British Columbia						
08HB048	Carnation Creek at the mouth	48°54'56"N	124°59'52"W	10.1	453	1972–2003
08HB014	Sarita River near Bamfield	48°53'34"N	124°57'54"W	162.0	535	1948–2003
08HB025	Browns River near Courtenay	49°41'33"N	125°05'07"W	86.0	982	1960–2003
08GA026	Capilano River above Eastcap Creek	49°27'14"N	123°06'33"W	69.9	1042	1926–2003
08MG025	Pemberton Creek near Pemberton	50°19'02"N	122°48'05"W	31.9	1550	1987–2003
08MH056	Slesse Creek near Vedder crossing	49°04'16"N	121°41'58"W	162.0	1300	1957–2003
08NL036	Whipsaw Creek below Lamont Creek	49°22'09"N	120°34'11"W	185.0	1553	1964–1998
08NM173	Greata Creek near the mouth	49°47'40"N	119°51'04"W	40.7	1435	1970–2003
08NM171	Vaseux Creek above Solco Creek	49°14'58"N	119°19'16"W	117.0	1829	1970–2003
08NE117	Kuskanax Creek at 1040 m contour	50°20'36"N	117°31'05"W	113.0	1761	1973–1996
08NH016	Duck Creek near Wynndel	49°12'10"N	116°31'56"W	57.0	1624	1921–2003
08NK026	Hosmer Creek above diversions	49°35'03"N	114°57'14"W	6.4	1784	1981–2003
08NK022	Line Creek at the mouth	49°53'29"N	114°50'00"W	138.0	2110	1971–2003
08NP004	Cabin Creek near the mouth	49°05'39"N	114°33'11"W	93.2	1919	1977–2003
Central British Columbia						
08OA002	Yakoun River near Port Clements	53°36'50"N	132°12'35"W	477.0	356	1962–2003
08FF003	Little Wedeene River below Bowbyes Creek	54°08'11"N	128°41'24"W	182.0	881	1966–2003
08JA015	Laventie Creek near the mouth	53°39'09"N	127°32'13"W	86.5	1900	1976–2003
08JA016	MacIvor Creek near the mouth	53°48'02"N	126°21'36"W	53.4	n/a	1976–1995
08JA014	Van Tine Creek near the mouth	53°15'48"N	125°24'30"W	153.0	1394	1974–2003
07EE009	Chuchinka Creek near the mouth	54°31'45"N	122°36'00"W	311.0	1089	1975–2003
08KE016	Baker Creek at Quesnel	52°58'23"N	122°31'11"W	1570.0	1200	1963–2003
08KH019	Moffat Creek near Horsefly	52°18'50"N	121°24'20"W	539.0	1348	1964–2003
08KA009	McKale River near 940 m contour	53°26'41"N	120°13'10"W	252.0	1919	1971–2003
08NC004	Canoe River below Kimmel Creek	52°43'41"N	119°24'30"W	298.0	2050	1971–2003
Northern British Columbia						
08CG006	Forest Kerr Creek above 460 m contour	56°54'56"N	130°43'15"W	311.0		1972–1994
10CD005	Adsett Creek at km 386.0 Alaska Highway	58°06'22"N	122°42'56"W	109.0		1983–2003
07FB005	Quality Creek near the mouth	55°08'45"N	120°55'24"W	29.5		1978–2001

We have attempted to focus on basins with drainage areas less than a few hundred square kilometres, as those are typically of greatest interest in forest management. The best data come from a transect through the southern part of the province at a latitude of about 49°30'N (Table 4.1; Figures 4.8 and 4.9).

The transect through central British Columbia (latitude 53°N; Figures 4.8 and 4.10) includes a similar number of stations, but their drainage basins are larger, on average, and less well distributed across the province. The third and final transect (Figures 4.8 and 4.10) describes the northern part of the province; however, few data can be found and only three suitable hydrometric records were identified.

Southern British Columbia

A generalized pattern of seasonal flow regimes for the southern part of British Columbia is described with reference to the monthly hydrographs for selected hydrometric stations (see Figures 4.8 and 4.9). To facilitate comparison between stations, the mean monthly discharge for each station is expressed as a depth of water (in millimetres) averaged over the basin area. The maximum and minimum recorded monthly values at each station for the period of record are also shown in Figure 4.9 to indicate the between-year range of mean monthly flows. To quantify the month-to-month variation in the mean monthly flows, we defined a "threshold low-flow" value. The threshold value is arbitrarily defined as 25% of the mean annual streamflow, expressed in millimetres per month (i.e., the mean annual streamflow divided by 12 months). All months where the mean monthly flow is less than the threshold low-flow value are indicated by a shaded area on the hydrograph for the relevant station in Figure 4.9. Regions where low flows fall below the threshold are likely susceptible to water shortages for human consumers and for the aquatic ecosystems that these rivers support; however, a detailed assessment of instream flow requirements requires a much more detailed analysis than can be achieved in this survey of the regional hydrology of British Columbia.

Vancouver Island

The hydrologic regime of the outer coast of Vancouver Island is described by hydrographs from two adjacent stations, Sarita River and Carnation Creek, both of which have rain-dominated regimes typical of relatively low-elevation, coastal basins. Carnation Creek has a smaller drainage area (10.1 km^2) than Sarita River (162 km^2), and a lower mean basin elevation (453 vs 535 m). The difference in their annual streamflow (3850 mm/yr for Sarita River compared with 2600 mm/yr for Carnation Creek) is consistent with the difference in mean elevation. The mean monthly flows are highest in November and December, when the discharge is about 400–600 mm. Mean monthly flows are lowest in July, August, and September (approximately 40–50 mm per month), when the discharge is about 10% of the mean flows recorded in November or December. The mean flows in July, August, and September fall below the low-flow threshold defined above. Basins on the outer coast, with a significant proportion of the basin area at high elevation (above approximately 1000 m asl), have annual streamflows similar to Sarita River, but exhibit a mixed-streamflow regime with a similar seasonal pattern to that for Browns River on the east coast of Vancouver Island. Since most of the mountain peaks on Vancouver Island are less than about 1800 m asl, no large basins have entirely snowmelt-dominated streamflow regimes. Many of the drainage basins on eastern Vancouver Island (e.g., characterized by Browns River) produce a mixed regime. Browns River exhibits high mean monthly flows in November and December as a result of storm-related precipitation, as well as a snowmelt-related peak in May. Low flows occur on average during August and September. The eastern part of Vancouver Island is effectively in the rainshadow of the island's outer coast, producing lower annual and monthly flows. For example, the annual streamflow for Browns River is about 2000 mm/yr, and the largest monthly flows (in November, December, and May) are between 200 and 300 mm. The effect of the snowpack on the seasonal regime of Browns River is clear in the comparatively high flows during June and July. By August, however, the mean monthly flows in Browns River are similar to those for the outer coast stations, averaging about 30 mm.

The stations on Vancouver Island all exhibit a high between-year range in flows for all months, which is typical of rain-dominated regimes. The minimum recorded monthly flow for all three stations is less than 10 mm in July, August, and September, and is less than 100 mm in all other months except for November and December, illustrating that low-flow conditions can occur in any summer month, and that the monthly flows in the early fall, winter, and spring can be well below the mean values for those months. The maximum recorded monthly flows for these three stations also indicate that any

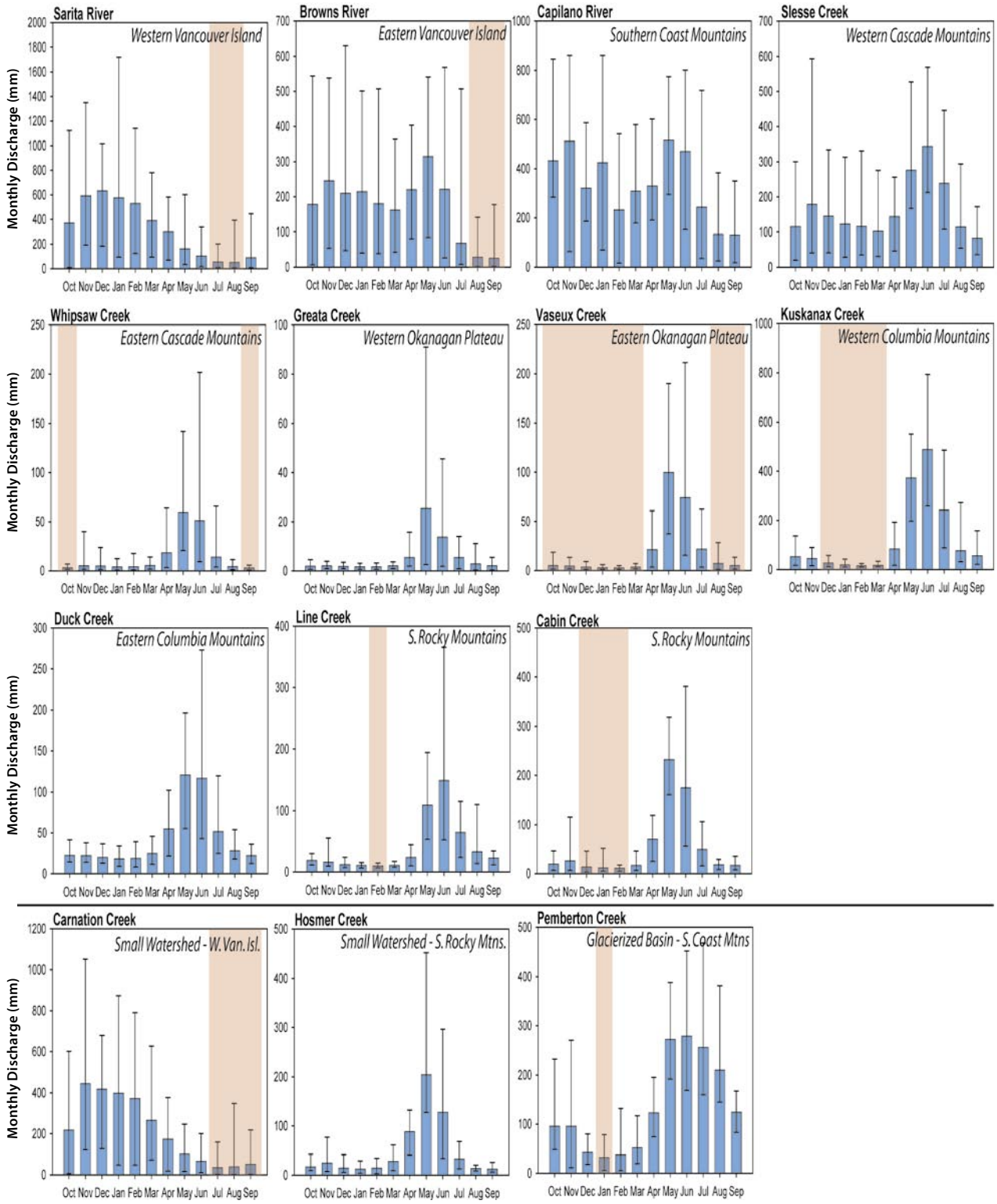

FIGURE 4.9 *Examples of average annual hydrographs for a transect of drainage basins across southern British Columbia. The height of the bars represents the multi-year mean streamflow for each month (millimetres per month); the error bar indicates the lowest and highest recorded monthly discharge in any year for the period of record.*

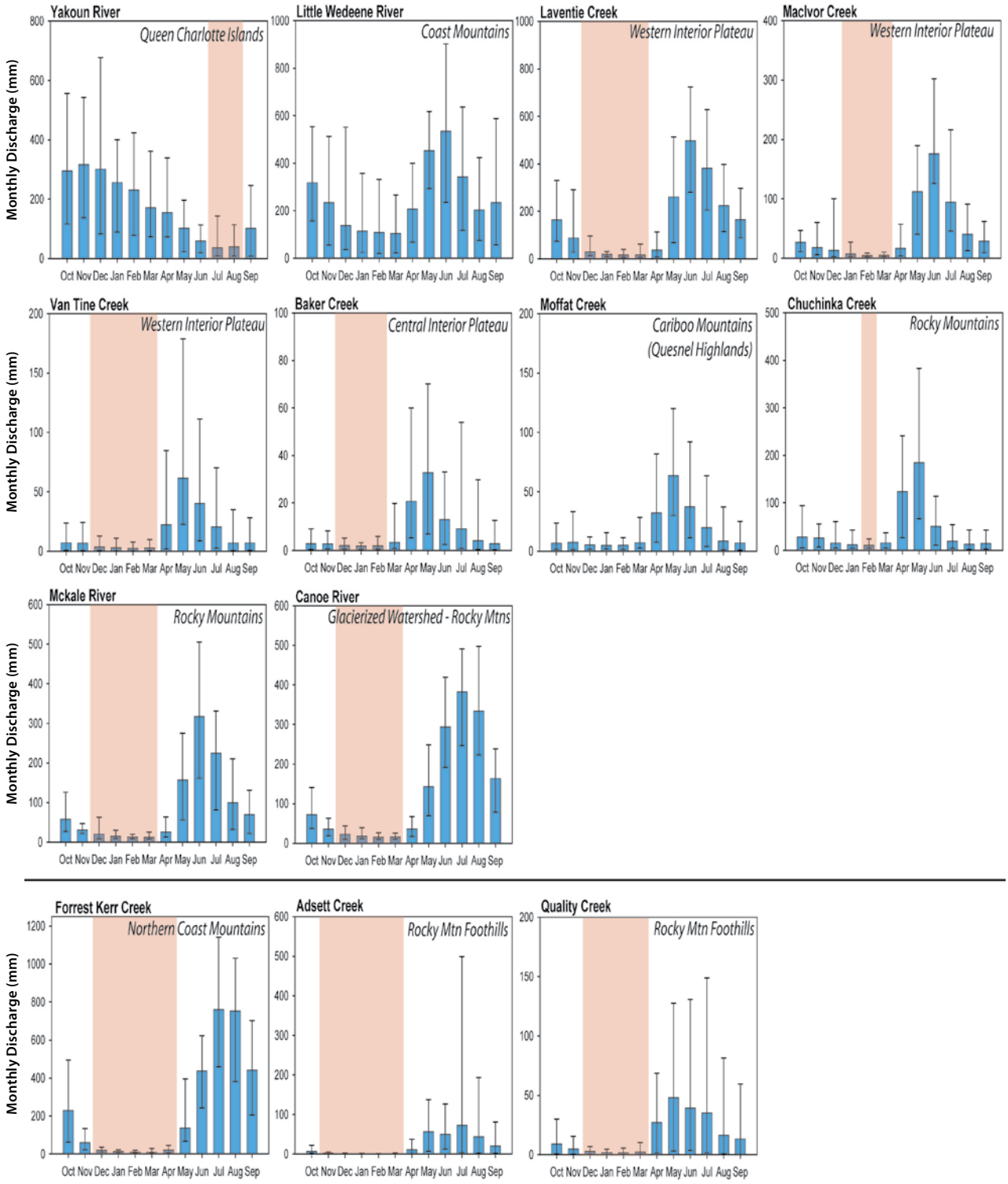

FIGURE 4.10 *Examples of average annual hydrographs for transects of drainage basins across central and northern British Columbia. The height of the bars represents the multi-year mean streamflow for each month (millimetres per month); the error bar indicates the lowest and highest recorded monthly discharge in any year for the period of record.*

month between October and March can be a "high-flow" month, having a flow greater than the highest mean monthly flow for the station. For the mixed-regime station (Browns River), any month except August and September can be a high-flow month.

Coast Mountains and Cascades

Across the Strait of Georgia, the height of the mountain peaks increases to 2000 m asl or more, resulting in an increase in orographic precipitation, a decrease in temperature, and an increase in the importance of the snowpack in the seasonal streamflow regime. Capilano River (above the Cleveland Dam) is a good example of the mixed-streamflow regime typical of basins in the Coast Mountains of southern British Columbia. The annual streamflow for this relatively high-elevation station (mean basin elevation is 1042 m) is similar to the outer coast of Vancouver Island (approximately 4000 mm/yr), as is the magnitude of the highest mean monthly flows (approximately 500 mm).

As expected for a mixed regime, the highest mean flows occur in November and May, in relation to heavy rainfall associated with frontal weather systems in the first instance and melting snow in the second. Low flows occur in August and September (having values of about 100 mm per month), but these flows do not typically fall below our definition of a threshold low flow. The between-year range is similar to that for the stations on Vancouver Island, and the highest recorded monthly flows for all months except August and September are greater than 500 mm. The record low monthly flows fall below 60 mm only in February, July, August, and September, indicating a reduced frequency of severe low flows, relative to Vancouver Island.

Slesse Creek occupies a similar environment, but is further inland from the coast and has a higher mean elevation (approximately 1300 m asl). Despite the higher basin elevation, the mean annual streamflow is about half that for Capilano River (approximately 2000 mm), similar to eastern Vancouver Island, reflecting the rapid decline in total precipitation with distance from the coast. The streamflow regime is dominated by snowmelt, producing a mean monthly peak of about 350 mm in June, although a smaller (approximately 180 mm), rain-related peak is evident in the mean monthly flow for November. The snowpack persists longer in the Slesse Creek drainage than in the Capilano watershed, and maintains relatively high flows (approximately 100 mm per month) even in August and September. The maximum recorded monthly flows exceed 350 mm only in November, May, June, and July, and the record low flows never fall below about 30 mm per month, indicating that the between-year range in seasonal streamflow is relatively low compared with stations that are more strongly affected by rain-related streamflow.

Some areas of the Coast Mountains are high enough and cold enough to be covered by glaciers. In these areas, snow and glacier melt dominate the seasonal streamflow pattern, though a weak rain-related streamflow component is evident in monthly discharge data. For example, Pemberton Creek (mean elevation of 1500 m asl) has a glacier covering roughly 25% of its drainage area. As a result, average high flows of between 200 and 275 mm per month occur in May, June, July, and August because of the seasonal melting of snowpack and glacier ice in the basin. Low flows typically occur from December to March, as precipitation contributes to snowpack storage and not streamflow. The record low flows indicate that only during the winter months, when most of precipitation is stored as snow and ice, do the flows ever drop below about 50 mm per month. The record high monthly flows for Pemberton Creek indicate that, although the highest mean monthly value (278 mm for June) is only ever exceeded during the glacier melt period, rainfall runoff generates smaller secondary monthly peaks in October and November.

The Cascade Mountains lie to the east of the Coast Mountains. Because precipitation declines rapidly with distance inland, as does temperature to a lesser degree, the Cascade Mountains are much drier than the Coast Mountains, particularly on their eastern aspects. For example, the annual streamflow for Whipsaw Creek is an order of magnitude less than any of the coastal drainage basins discussed above (approximately 180 mm/yr). The streamflow regime is strongly dominated by snowmelt, with more than half the total annual streamflow occurring in May and June. From August to March, the mean monthly flows are less than 6 mm, with record low flows below 2 mm for the same period. The mean monthly flows for September and October fall below the low-flow threshold. The record high flows exceed about 50 mm per month during April, May, June, and July alone, reflecting the variable timing of seasonal snowmelt and possibly the varying role of rainfall during the snowmelt freshet. The record monthly flow for November, about 40 mm, is the only evidence of a rain-related streamflow regime.

Interior Plateaus

The Interior Plateaus west of the Okanagan Valley are even drier than the eastern slopes of the Cascade Mountains. Greata Creek, draining off the plateau into Okanagan Valley near Summerland, has a mean annual streamflow of only 70 mm, despite having a mean basin elevation similar to Whipsaw Creek. High flows caused by snowmelt occur during May and June, falling to less than 3 mm per month between August and March. The record low monthly flows for every month are less than 3 mm, indicating that in some years, almost no snowmelt-generated streamflow occurs. Despite this, none of the mean monthly flows falls below the low-flow threshold because the annual streamflow is so low. Conversely, the record high monthly flow for May (91 mm) exceeds the mean total annual streamflow. In this relatively arid environment, the between-year range is large in the streamflow regimes.

The Interior Plateaus east of the Okanagan Valley are slightly higher, and tends to accumulate deeper snowpacks, producing slightly higher annual streamflow. Vaseaux Creek has a mean annual streamflow of about 250 mm, similar to Whipsaw Creek in the Cascades. The mean seasonal pattern and between-year range are similar to Greata Creek, with record high flows for May and June approaching the mean total annual streamflow volumes and a fairly narrow range of low flows between August and March; however, the mean monthly flows for all months between August and March fall below the threshold low flow, indicating persistent and severe water limitations for most of the year in this part of British Columbia.

Columbia Mountains and Rockies

East of the Interior Plateaus, the Columbia Mountains rise to more than 2500 m asl. These ranges induce another phase of orographic precipitation, resulting in higher annual streamflow values than on the plateau. This region of British Columbia is represented by Kuskanax Creek, which has an annual streamflow of about 1500 mm, of the same order as values at the coast and much greater than those for the Interior Plateaus. The monthly discharge for May and June is on average between about 400 and 500 mm, which is equivalent to the highest mean monthly for the coastal stations. Unlike the coast, however, flows of this magnitude only ever occur during the snowmelt season between May and July. Typically, flows decline more or less continuously after the peak in June, reaching threshold low-flow levels between December and March.

For Kuskanax Creek, the between-year range of monthly flows in May and June is relatively small, and is typically about ± 50%. Since the coastal basins with a dominant snowmelt component have similar ranges for May and June, this relatively conservative behaviour seems typical of humid, snowmelt-dominated streamflow regimes. The more arid parts of the province may have a greater year-to-year variation in snowpack, and consequently in the range of monthly flows, as at Greata Creek. The annual streamflow regimes for Duck Creek (520 mm), Line Creek (480 mm), and Cabin Creek (660 mm) illustrate the west-to-east trend through the Columbia and Rocky Mountains. Duck Creek flows west into Kootenay Lake near Creston; Cabin Creek flows east into the Flathead River near the British Columbia–Alberta border; and Line Creek flows west from the border into the Elk River north of Sparwood. The streamflow regimes for all three stations are similar in pattern and magnitude, and indicate a snowmelt-dominated streamflow regime with a fairly small year-to-year variation in the monthly flows. Although the highest mean monthly flow for these stations occurs variously in May or June, the highest monthly value on record for all stations invariably occurs in June. This implies that the largest monthly flows in snowmelt regimes are a result of the delayed melt of a substantial snowpack. In fact, the highest monthly flow on record occurs in June for all of the snowmelt-dominated stations except for Greata Creek, which has the lowest mean elevation of all the snowmelt-dominated stations on the southern transect.

The streamflow regime for Hosmer Creek (near Line Creek) is presented to illustrate the effect of scale on snowmelt-dominated seasonal streamflow regimes. The main difference between Hosmer Creek and Line Creek is the occurrence of both the highest record and highest mean monthly flow in May rather than in June, a result of the somewhat lower mean basin elevation (Table 4.1). In addition, Hosmer Creek's basin has a maximum elevation of about 2200 m, over 1000 m less than that for Line Creek. Thus, the timing of the peak monthly flows probably reflects the earlier onset of snowmelt at lower elevations.

Central British Columbia

The seasonal flow regimes for Central British Columbia are described with reference to the monthly hydrographs for the hydrometric stations shown in Figure 4.10. The variation from west to east is roughly similar to that for the southern transect, but reflects systematic differences in climate, linked to the higher latitude, and in the physiography.

Haida Gwaii

Streamflow regimes on Haida Gwaii (previously known as the Queen Charlotte Islands) are described by the monthly hydrograph for Yakoun River, which has an annual streamflow of 2060 mm. The pattern of peak and low flows and the between-year range for each month are similar to those for Sarita River and Carnation Creek on Vancouver Island to the south. The monthly flows (both mean and maximum) are slightly lower for Yakoun River, reflecting its lower mean basin elevation and its position some distance inland from the exposed west coast. The basins on the exposed west coast likely have monthly discharge values at least as high as that for Sarita River. A shift is also apparent in the beginning of the rainy season for Yakoun River, where the monthly flows for October are almost as high as those for November and December. Given the relatively low elevation of the Queen Charlotte Ranges, the seasonal streamflow regimes for nearly all of the drainage basins on Haida Gwaii are likely dominated by rain.

Coast Mountains

East of Haida Gwaii, the coast of the British Columbia mainland rises steeply, culminating in mountain peaks slightly lower than those in the southern Coast Mountains. Little Wedeene River, near Kitimat, has a relatively high annual streamflow of about 2990 mm, similar to Capilano River in the south. Little Wedeene River exhibits a mixed regime, with both rain- and snowmelt-related monthly peak flows. Despite having a lower mean elevation than the Capilano basin (881 vs 1042 m asl), Little Wedeene River exhibits a stronger snowmelt component, and the highest monthly flows (mean and record) occur in June. A shift in the timing of the rain-related peak monthly flows is also apparent, with the maximum occurring in October rather than November. These differences are attributable to climatic gradients associated with latitude, which result in a colder climate with earlier onsets of both wet weather and the shift from rainfall to snowfall in central British Columbia.

Interior Plateaus

Moving inland, the terrain grades into a high plateau with fairly low relief that slopes gently toward the Fraser River to the east. The mean basin elevations for Laventie, MacIvor, Van Tine, and Baker Creeks reflect this general physiography. The seasonal streamflow patterns for all of these stations are dominated by snowmelt. The total mean annual streamflow declines from west to east, with values of 1900, 540, 180, and 100 mm for Laventie, MacIvor, Van Tine, and Baker Creeks, respectively. The timing of the maximum monthly flows also changes. For the higher-elevation stations (Laventie and MacIvor Creeks), the maximum occurs in June, fed by relatively high-elevation snowpacks. For the lower-elevation stations (Van Tine and Baker Creeks), the peak occurs in May. All of these stations typically experience extended periods of low flows below the low-flow threshold during the winter months. In fact, this is generally true for all snowmelt-dominated regimes at this latitude. The between-year range of variability (based on the record high and low flows for each month) also varies consistently, and tends to become relatively larger (as a percentage of the mean) as the streamflow declines from west to east.

Cariboo Mountains and Rockies

East of the Fraser River, the terrain rises again, forcing an increase in the amount of precipitation. Moffat Creek, in the Quesnel Highlands, has a mean basin elevation similar to Van Tine Creek. It also has a very similar seasonal streamflow regime, and total annual streamflow (200 mm for Moffat Creek vs 180 mm for Van Tine Creek). McKale Creek in the Rocky Mountains is much higher and wetter, with an annual streamflow of 1040 mm. The Rocky Mountains at this latitude are not shielded by high mountains to the west, as they are in the south, and therefore the mean annual streamflow is about twice that for basins in the south. As expected for basins at relatively high elevation, the high flows for McKale Creek occur in June. Where glaciers exist (see Canoe River, annual streamflow of 1540 mm), the annual streamflow is higher—the result of an orographic precipitation effect—and the highest flows occur in July, with high flows occurring from May right through to the end of September.

There are local, physiographically related deviations from this west to east pattern. For example, Chuchinka Creek (54°30'N) is in a physiographic position similar to Moffat Creek to the south. Despite a lower mean basin elevation, however, it has nearly twice the mean annual streamflow (510 mm) of Moffat Creek. This difference is likely because the Coast Mountains decline in height from Bella Coola (52°30'N) to Prince Rupert (54°30'N), thereby having a reduced effect on weather systems tracking in from the North Pacific at the higher latitudes.

Northern British Columbia

The physiography of northern British Columbia differs from that to the south. The Coast Mountains increase in height north of Prince Rupert, which, combined with the latitudinal effect on the mean annual temperature, results in extensive alpine glacier cover. The seasonal streamflow regime for Forrest Kerr Creek (2890 mm) is probably typical of the drainage basins near the western border of northern British Columbia (Figure 4.10). The highest monthly discharge of these basins occurs in July and August, with virtually no flow during the cold winter months when most of the incoming precipitation is stored in the basin as snow and ice.

Unlike the southern parts of British Columbia, no well-defined interior plateau occurs east of the Coast Mountains, except for the relatively limited Stikine Plateau in the northwest corner of the province. Instead, one encounters first the Omineca and Cassiar Mountains, and then the northern Rocky Mountains. Glacier cover is limited in these mountain ranges, which typically exhibit a snowmelt-dominated regime. The available data are too sparse to describe the pattern of variation across these mountain ranges, but the mean annual streamflow on the eastern slopes of the Rocky Mountains falls to about 200–250 mm. The seasonal streamflow patterns for Adsett Creek (270 mm/yr) and Quality Creek[1] (200 mm/yr), which are both relatively low-relief drainage basins verging on the Alberta Plateau, indicate that the peak streamflow months occur between May and July, which is slightly later than for stations to the south. In fact, the highest monthly discharge on record for both stations occurs in July, whereas it occurs consistently in May or June for the snowmelt-dominated regimes in southern and central British Columbia. Snowmelt in these low-relief basins consistently peaks in May, and the high flows in June and July are attributable primarily to frequent rain produced by frontal systems moving south from the Arctic Ocean. The winter flows are also lower than to the south, with almost no streamflow occurring from November to March.

PEAK FLOWS

Stream channel dimensions are largely formed during the highest flows regularly carried by a stream channel. One common way of indexing these flows is by using the peak daily or peak instantaneous discharge occurring in a given year. The design of any stream crossings or instream structures, such as fish habitat enhancements, must consider the magnitude and frequency of these so-called channel-forming flows. The mechanisms that produce peak flows vary systematically across the province. Since land use activities are often managed based on assumptions about the way in which human activities (e.g., forest harvesting or road building) influence peak flows, it is important to understand how, when, and why these peak flows actually occur. The differences between the Coastal Watershed Assessment Procedures and the Interior Watershed Assessment Procedures described in the original *Forest Practices Code of British Columbia Act* were based primarily on the assumption that rain or rain-on-snow events produced floods at the coast, whereas snowmelt events produced floods in the Interior. Because more than one flood-generating mechanism can affect a given basin, it is probably inappropriate to classify watersheds as simply "coastal" or "interior" types, particularly in northern British Columbia where summer rain events seem to produce nearly all of the largest peak flows.

1 Although Quality Creek is relatively close to latitude 53°N, it is on the east side of the continental divide and is controlled by weather patterns typical of northern rather than central British Columbia. The scarcity of data in the northern part of the province requires that this station be included in what is an already sparse data set.

Regional Variations

The factors controlling peak flow magnitude are the same as those controlling the seasonal streamflow regime—that is, precipitation inputs and storage of water within a drainage basin. In British Columbia, peak flow events can be produced by rainfall, snowmelt, and glacier melt, and by combinations of these mechanisms. For example, rain-on-snow events commonly occur at intermediate elevations in coastal montane areas. In these events, melting of snow accumulated during earlier, colder storms contributes to streamflow in addition to rainfall, typically increasing the resulting peak flow. The main difference between the mechanisms generating peak flows and the factors controlling the seasonal streamflow regime is the time scale over which the processes act, rather than the processes themselves. In addition, glacier outburst events and breaching of moraine-dammed lakes can cause peak flows (Church 1988); however, these events are not influenced by forest management and are not addressed further. For more detailed coverage of peak flow generating mechanisms and the effects of forest harvesting, see Chapter 6 ("Hydrologic Processes and Watershed Response") and Chapter 7 ("The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response").

Comparisons of peak flows among basins of different drainage areas are difficult because the mean annual peak flow per unit area is not constant, even in hydrologically homogeneous zones. Smaller drainage basins typically exhibit higher peak flows per unit area than larger ones. To make a scale-independent comparison across the province, this scale effect needs to be removed by expressing the mean annual peak flow per unit area as a k factor, defined as:

$$k = \frac{Q_{peak}}{(A_d)^{\beta}}$$

where: Q_{peak} is the peak flow, A_d is the drainage area, and β is an exponent to account for the scale effect; in British Columbia, β is about 0.75. Figure 4.11 presents a map of k factors for the mean annual peak flow across British Columbia. See Eaton et al. (2002) for the details of the underlying analysis and a discussion of the limitations, as well as maps of k factors for the 5- and 20-year return period peak flows. For our purposes, it is sufficient to interpret the k factors in Figure 4.11 as measures of the mean annual peak flow per unit area for basins with the same drainage area, specifically 1 km^2. The maps for the 5- and 20-year floods are similar to those for the mean annual flood (k_{maf}), varying primarily in the absolute magnitude of the k value.

An analysis of the average ratio of k_{20} to k_{maf} by region shows that the largest differences occur where rain and rain-on-snow events produce floods and the smallest differences occur where snowmelt is the primary flood-generating mechanism (Eaton et al. 2002).

The text in the following paragraphs describing the k factor map are reproduced from Eaton et al. (2002) and only slightly modified. Figure 4.11 illustrates some fundamental aspects of British Columbia regional hydrology. The major pattern of peak flows follows the structural–topographic grain of the province that controls the distribution of precipitation (see precipitation map in Chapter 3, "Weather and Climate") and is also reflected in regional patterns of annual streamflow (e.g., see Waylen and Woo 1982a, for a map of streamflow patterns in the Fraser River basin, which encompasses most of southern British Columbia). The coast has substantially higher streamflow than anywhere else, resulting from frequent storms originating in the Pacific Ocean, which subsequently encounter the mountainous coast.

The gradients in the parameter k are steep along the entire coast, where values range from about 1 to more than 8. This steep hydrologic gradient is primarily due the relatively intense orographic uplift associated with the Coast Mountains.

The plateaus of the southern and central Interior have relatively low peak flows, with flows nearly two orders of magnitude less than in the wettest parts of the coast. The interior plateaus have characteristically low relief, and are strongly influenced by the rain-shadow produced by the Coast Mountains; however, the hydrologic gradients in the interior plateaus are even steeper than along the coast. The k values range from less than 0.1 in the centre of the plateaus to 1 along the eastern and western margins. Low peak flows also occur on the Alberta Plateau in the northeast part of the province.

The eastern Cordillera (Rocky Mountains and Columbia Mountains), where substantial orographic uplift occurs again, has k values between 1 and 2. The floods generated in this part of British Columbia are more strictly limited in between-year variability (ultimately, by the energy available for snowmelt) than are rainstorm-generated floods typical along the coast. The hydrologic gradients are much less strong here, reflecting primarily the influence of the relatively high (and wet) Columbia Mountains.

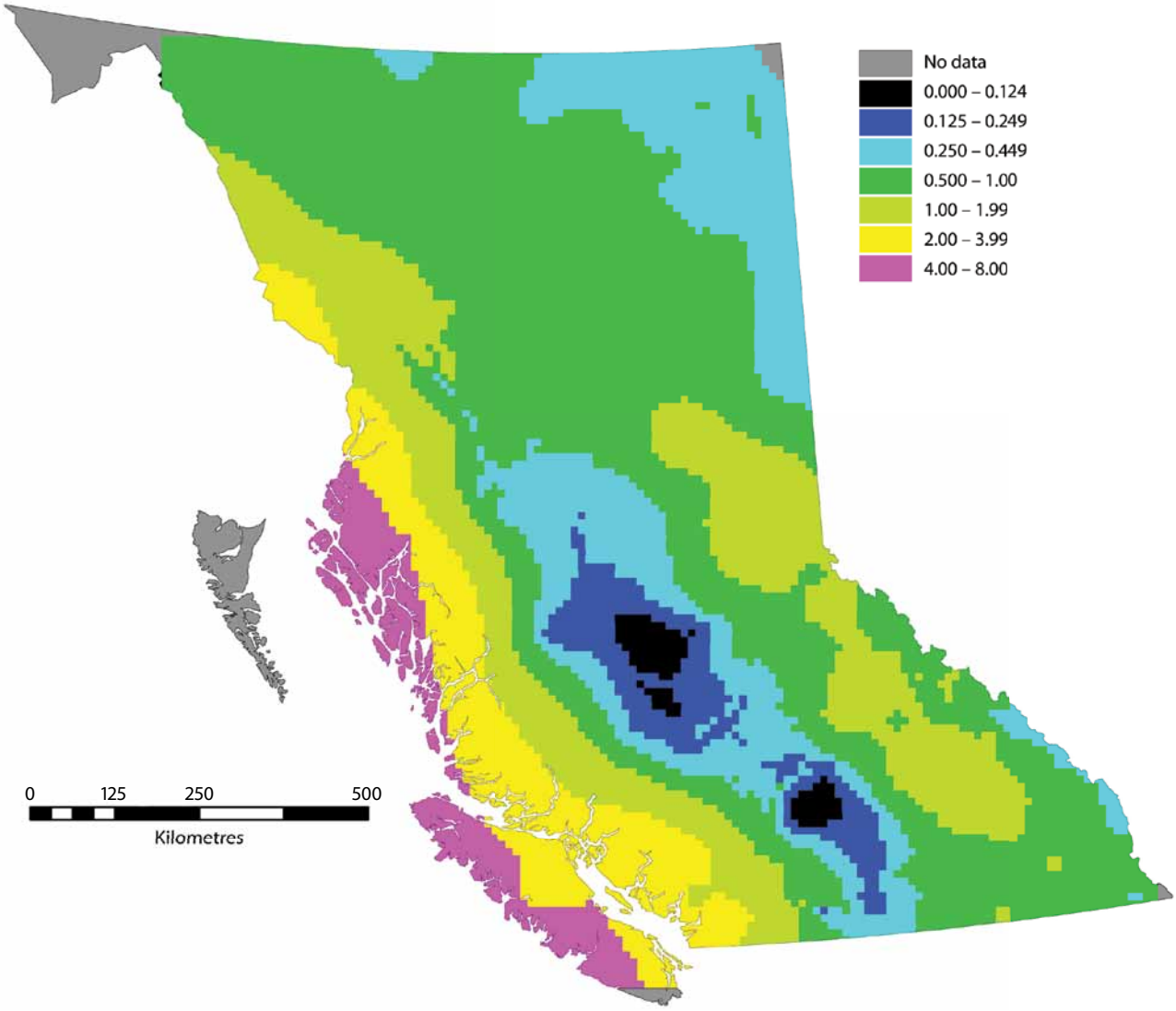

FIGURE 4.11 *Map of* k *factors, representing the pattern of mean annual peak flows over British Columbia.*

Peak Flow Timing and Mechanisms

Low-relief coastal basins

For basins where the seasonal streamflow regime is dominated by rainfall inputs (e.g., Carnation Creek and Sarita River in the south; Yakoun River in central British Columbia), the annual peak flows typically occur in the fall and winter (see Figure 4.12). On the central coast of British Columbia, annual peak flows may occur earlier than on the south coast, often in mid- to late September; in the south, these flows typically do not occur before mid-October. Annual peak flows in these rain-dominated drainage basins generally occur no later than the end of February, both in the southern and central coastal regions of British Columbia. The peak flow dates appear to be fairly uniformly distributed throughout this period, and the annual peak flow magnitude shows no systematic trend.

The highest annual peak flows in many coastal drainage basins most likely result from warm frontal systems combined with a wet snowpack; thus, melting of the snow and the inputs of large volumes of rain both contribute to the peak flow. These "rain-on-snow" events will be more common for basins at moderate to higher elevation, but will occasionally occur in the low-elevation coastal basins.

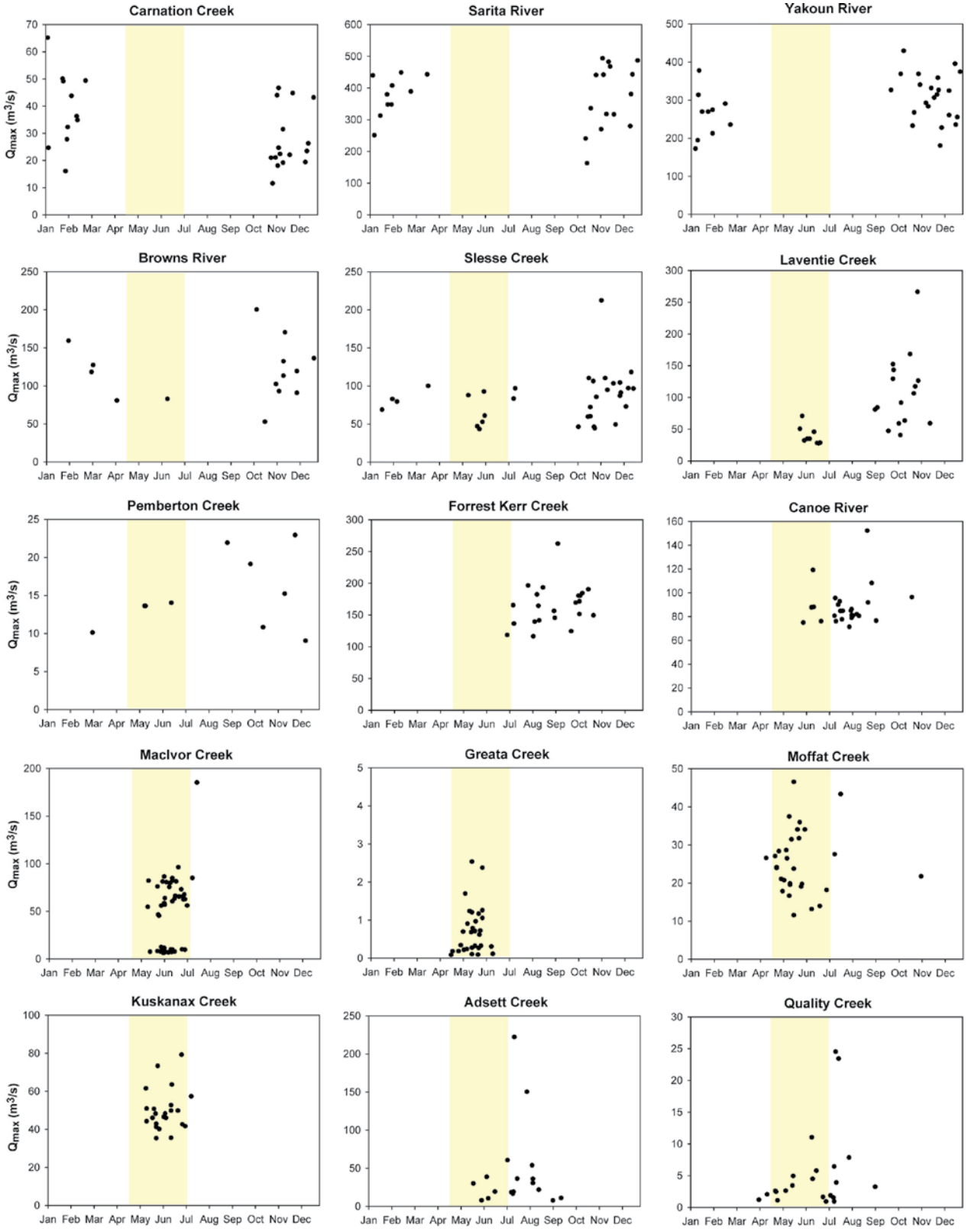

FIGURE 4.12 *Temporal distribution of annual peak flows for a selection of British Columbia drainage basins.*

High-relief coastal basins

The coastal stations with significant snowmelt contributions to their seasonal streamflow regimes (Browns and Slesse Creeks in the south, Laventie Creek in central British Columbia) may be subject to annual peak flows over many months in response to various peak flow generating mechanisms. Annual peak flows may occur in the fall in these environments as a result of rain events, occurring as early as September in central British Columbia and October in southern British Columbia. These cyclonic rain events occur less frequently in the winter, especially in central British Columbia, because much of the incoming precipitation is stored in high-elevation snowpacks and so does not immediately produce streamflow. Another distinct population of peak flows occurs in May, June, or July in response to seasonal snowmelt, when the water stored in the snowpack is released; however, the highest annual peak flows on record for Browns, Slesse, and Laventie Creeks invariably occurred in October or early November. These peak flows are likely the result of an early snowfall, followed by a warm frontal system producing rain-on-snow events that are much larger than those that could be generated by either rain or snowmelt events alone. Since various mechanisms can generate peak flows, the timing and magnitude of the peak flow in any given year are difficult to predict. Note that some coastal basins contain significant glacier cover, the effect of which is described separately below under the heading of glacierized basin.

Interior basins

The interior parts of British Columbia that are not influenced by glaciers exhibit a more predictable peak flow timing that usually depends on both elevation and latitude. The peak flows are frequently generated by snowmelt, although peak flows related to convective rainstorms do occur occasionally, and may indeed produce some of the largest flood events. For snowmelt events, the peak flow magnitude depends on the amount of water stored in the snowpack and the climatic conditions producing melt; for floods produced by convective storm cells, the degree of surface heating and availability of moisture determine the intensity and duration of the rainstorm and hence the magnitude of the flood.

In general, snowmelt-dominated peak flows in central and southern British Columbia occur between early May and late June (see MacIvor Creek, Figure 4.12), although both mean basin elevation and snowpack depth modulate the peak flow timing. Lower-elevation stations, such as Coldstream Creek (Figure 4.13), may experience annual peak flows as early as April and typically no later than late May (Greata and Moffat Creeks, Figure 4.12). The earlier peak flows tend to be smaller, reflecting a relatively small winter snowpack that is quickly exhausted with the onset of temperatures high enough to initiate seasonal snowmelt. The largest events in these basins occur in mid- to late May, and are generated from a snowpack that persists long enough to experience higher daily temperatures and solar radiation, leading to accelerated melt rates. Higher-elevation basins that develop deeper snowpacks typically experience peak flows between early May and early July (see Kuskanax Creek, Figure 4.12; Harper Creek, Figure 4.13). This shift in peak flow timing is the product of lower mean daily temperatures (and thus melt rates) at higher elevations and deeper snowpacks that persist into the warmer summer months. In many of these basins, convective storms in June, July, and August may either augment snowmelt-generated streamflow (Coldstream Creek, Figure 4.13), or produce entirely rainstorm-driven floods (Vaseaux and Van Tine Creeks, Figure 4.13).

In the northern part of the province, the timing of the peak flows is more variable, usually occurring between May and July, and sometimes as late as August, as illustrated by Adsett Creek (Figure 4.13). This shift is attributable to climatic differences, whereby frequent, large convective rainstorms in the northeastern part of British Columbia typically produce most of the significant flood events.

Glacierized basins

In drainage basins that have significant glacier cover, intense melting of glacier ice in the summer drives a distinct population of floods, which are superimposed on the rain, rain-on-snow, or snowmelt-generated peak flow regimes that are otherwise typical of the region. For instance, the annual peak flows at Pemberton Creek can occur in May or June in response to snowmelt, in August or September in response to glacier melt, or in October, November,

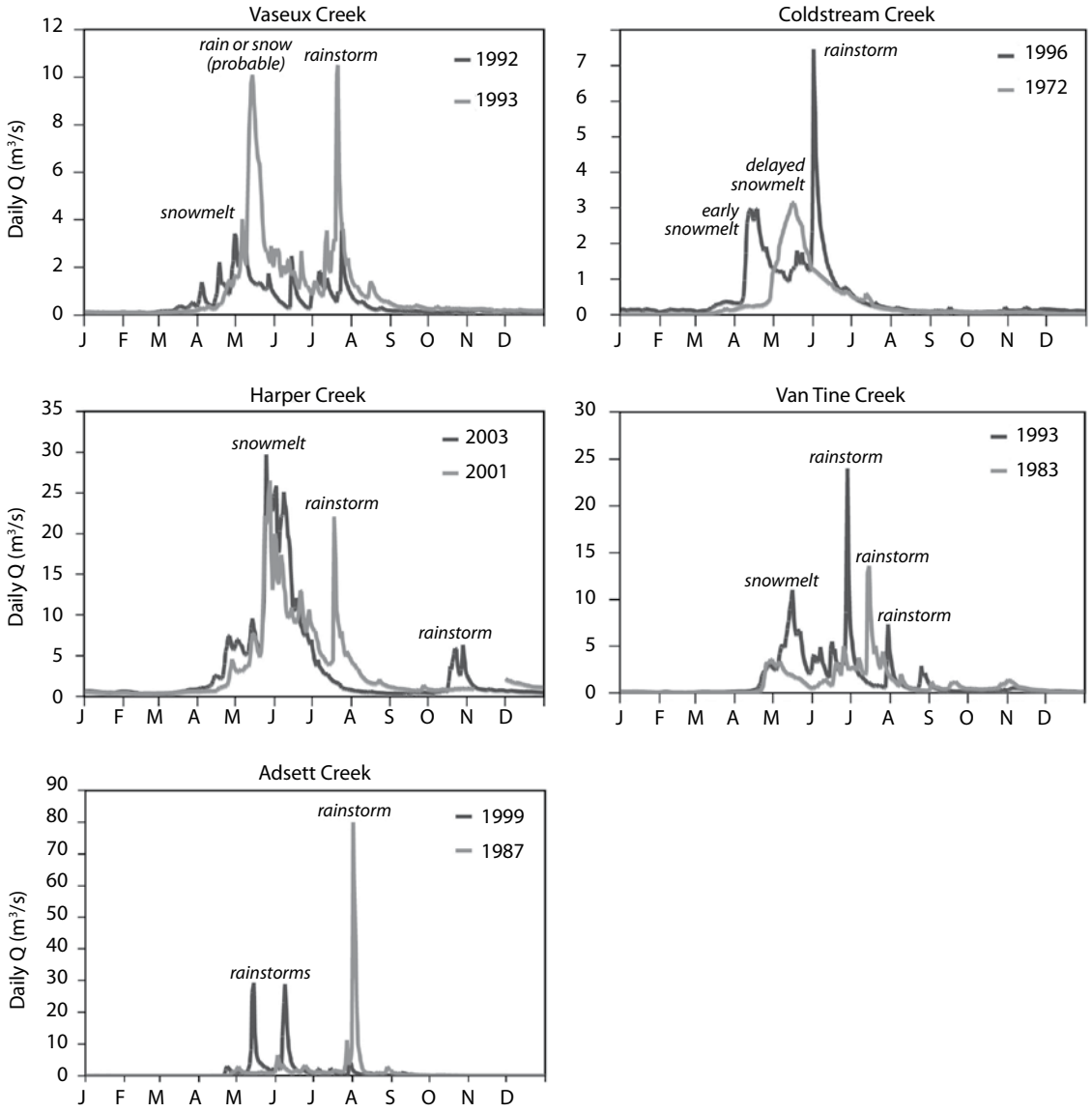

FIGURE 4.13 *Daily data for various hydrometric stations illustrating the range of possible flood-generating mechanisms throughout interior British Columbia.*

and December as a result of warm frontal systems producing rainfall with melting of either glacier ice or an early snowpack. In the northern part of the province, Forrest Kerr Creek also experiences annual peak flows between June and late October, likely as a result of snowmelt, glacier melt, or rain-on-snow peak flow generating mechanisms.

In the Rocky Mountains, the timing and generation of peak flows in glacier-covered basins is similarly variable: Canoe Creek may peak in May or June as a result of snowmelt, or peak in July, August, or September as a result of glacier melt. A rain or rain-on-snow event occurred in Canoe Creek during October.

STREAMFLOW SENSITIVITY TO CLIMATIC CHANGE

Several studies have examined the potential effects of future climate change, usually employing scenarios based on output from general circulation models (also increasingly known as "global climate models"). As noted in Chapter 3 ("Weather and Climate") and Chapter 19 ("Climate Change Effects on Watershed Processes in British Columbia"), the models all generally predict warming, though they vary greatly in the amount of warming and its seasonal expression, and do not agree in relation to precipitation.

The effects on rain-dominated systems should broadly reflect the changes to rainfall patterns (Loukas et al. 2002). For nival regimes, especially in southern British Columbia, the warming trend should result in a shorter snow accumulation season with an earlier freshet, resulting in lower flows in late summer and early autumn (Loukas et al. 2002; Merritt et al. 2006). Indeed, some model scenarios suggest that Fraser River, currently a nival regime, may become more rainfall-dominated as a result of future warming (Morrison et al. 2002). For hybrid regimes, the nival component should become weaker or even non-existent, resulting in more winter rainfall and lower spring–summer flows, attributable to the loss of seasonal snowmelt contributions. Glacial regimes may be less affected by climatic change in the early stages of warming, as increased melt could enhance glacier runoff. In the longer term, however, glacier retreat would result in less ice area available for melt, and thus declining streamflow contributions. In fact, Stahl and Moore (2006) found that glacier-fed streams in British Columbia dominantly exhibited negative trends in August streamflow since the 1970s, a period marked by significant glacier recession in many regions.

SUMMARY

The seasonal streamflow regime and peak flow characteristics vary systematically across British Columbia as a result of systematic variations in precipitation and the way in which precipitation is stored and released once it reaches the ground surface. The seasonal streamflow regimes can be broadly classified into regimes dominated by inputs of precipitation as rain, regimes dominated by runoff generated by melting snow or glacier ice, and regimes that reflect both rain and melt contributions.

Rain-dominated regimes characteristically have higher flows during the fall and winter, when a persistent low-pressure system brings storms over British Columbia from the Pacific Ocean. Low flows occur during the summer as a result of the development of a persistent, blocking high-pressure system that directs storms to the north of British Columbia, and basins with rain-dominated regimes appear most susceptible to water shortages overall, especially during the growing season. Since the sequence of weather systems that occurs drives streamflow in these basins, the seasonal streamflow pattern varies substantially from year to year, and seasonal streamflows for a given year are no more predictable than the weather.

Snowmelt-dominated regimes characteristically exhibit high flows in May or June as a result of melting snowpacks, and low flows in the winter, when precipitation is accumulating on the ground as snow. Low flows can also occur in late summer or early autumn. Glacier-melt regimes are similar to snowmelt regimes, but melt-related high flows persist into the hottest summer months. The seasonal streamflow pattern for these basins does not vary much from year to year because the basins effectively integrate the weather-driven precipitation inputs over the fall and winter, and then release the stored water in the spring and summer, often overwhelming any weather-driven inputs of rain.

The spatial distribution of these regime types throughout British Columbia is determined primarily by the elevation of a drainage basin and the distance of the drainage basin from the coast; it is influenced to a lesser degree by the latitude of the drainage basin. Generally, the low-elevation coastal basins have a seasonal streamflow regime dominated by rainfall whereas the drainage basins in the Interior exhibit a snowmelt regime. High-elevation drainage basins near the coast often exhibit a mixed regime, showing components of both the rain and

snowmelt regimes. The highest-elevation basins on the coast and in the Interior tend to contain glaciers, producing a glacier-melt regime. The local physiography also affects the characteristic streamflow regimes. For example, basins on the plateau tend to accumulate modest snowpacks that melt everywhere at nearly the same time, producing small annual streamflow values, but a short, steep snowmelt hydrograph. In contrast, mountainous drainage basins tend to intercept considerably more precipitation than the plateaus because of orographic uplift; however, snow melts first at the lower elevations and later in the season at higher elevations, producing high annual streamflow values with a longer, gradual snowmelt hydrograph.

Peak flows follow a similar geographic pattern, and can be generated by rain events, snowmelt, glacier melt, or some combination of rain and melt inputs of water. Typically, rain and rain-on-snow events are dominant on the coast, whereas melt or rain-on-snow events are dominant in the Interior. Rain events produce peak flows in nearly all drainage basins throughout British Columbia, and in some areas (particularly in northern British Columbia) may produce almost all of the largest flood events. Most drainage basins in British Columbia exhibit a mix of flood-generating mechanisms, which is significant for flood frequency analysis.

Conventional methods as described in standard textbooks (e.g., Linsley et al. 1982) assume that a single, common mechanism (e.g., seasonal snowmelt) generates all floods. It is more appropriate, although less common, to apply methods that acknowledge and account for heterogeneous flood-generating mechanisms (Waylen and Woo 1982b; Alila and Mtiraoui 2002).

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