4. Processes and Regimes

4.1 Introduction

Low flows occur after periods of low rainfall or when precipitation falls as snow. This results in a reduction in water stored in soils, aquifers and lakes and a decrease in the outflow to the river. The timing of depletion depends primarily on antecedent weather conditions. The rate of depletion depends on hydrological processes and the storage properties within the catchment.

This chapter presents a summary of how these factors control the spatial and temporal distribution of low flows. An understanding of these flow-generating processes can aid the following:

(a) The establishment of data requirements for a low-flow investigation (section 3.3);
(b) The assessment of the variability of low flows in a catchment;
(c) The selection of the most appropriate low-flow analyses method from those described in this Manual;
(d) The development of hydrological models;
(e) The interpretation of results.

Figure 4.1 shows the model of a catchment that receives precipitation, which then recharges different catchment storages, that is, soil water, groundwater, snow, glaciers, wetlands and lakes. The outflow from each of these storages contributes to river flow.

4.2 Processes causing low flows

4.2.1 Climate drivers

Catchment inputs originate from rainfall or snowmelt; thus, decreases in input can be caused by either:

(a) An extended dry period leading to a climatic water deficit when potential evaporation exceeds precipitation; or

(b) Extended periods of low temperatures during which precipitation is stored as snow.

Low flows usually occur during a long spell of warm, dry weather typically associated with high pressure systems and subsiding air. High temperatures, high radiation input, low humidity and wind increase evaporation and transpiration rates. Snowfall and snow storage result from temperatures continuously below freezing which are often associated with cold, polar air masses and/or decreasing temperatures at higher altitudes. In the absence of snowmelt, precipitation will accumulate and this will lead to a reduction in low flows.

In many regions, one or both situations occur annually. In mid- and high-latitude climates, low flows are often described by the season of occurrence, namely "summer low flow" and "winter low flow" (Figure 4.2). In low latitude climates, there may be one or more dry season and, consequently, one or more distinct low-flow period. As a result of constantly high evaporation rates, the climatic water deficit from the dry season may persist

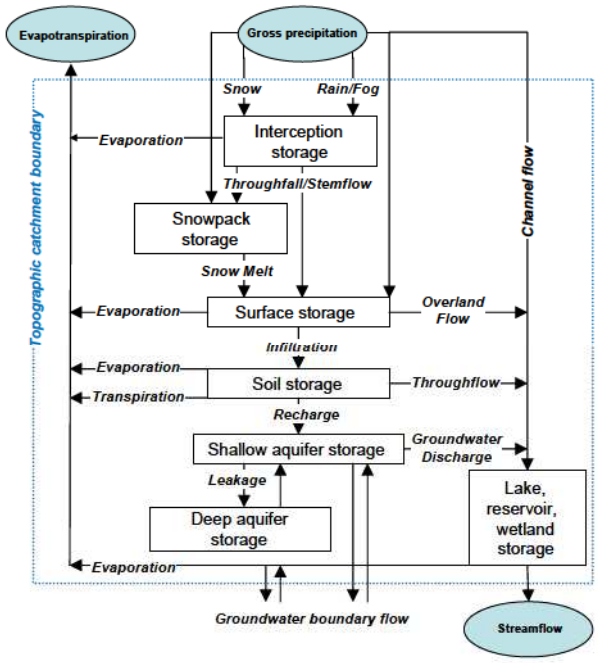

Figure 4.1 *Hydrological processes and catchment storages (modified from Tallaksen and van Lanen, 2004)*

Figure 4.2 *Summer and winter low flows*
(left: Dreisam River, Freiburg, Germany, August 1998; right: Columbia River, Golden, Canada, February 2007)

into the wet season. In arid and semi-arid climates, the combination of low precipitation and high evaporation results in minimal river networks and ephemeral rivers. These typically have prolonged periods of zero flow over several months or years and episodic high flows often in the form of flash floods.

Climate determines the magnitude and variation of temperature, precipitation and potential evaporation over the year. Climate diagrams and maps provide a valuable source of information for assessing the climatic drivers and the expected timing of low flows. However, climate varies spatially, particularly in mountain regions where there are strong altitude-dependent temperature and precipitation gradients. High precipitation (as rain or snow) in mountainous areas is often critical for providing the source of downstream low flows in arid or semi-arid areas. Climate also varies temporally at inter-annual, decadal and even centennial timescales. Long-term trends and changes in the climate system will result in changes to the low-flow regime.

4.2.2 Catchment processes and storage

While climate controls may lead to a climatic water surplus in one season and a deficit in another, catchment processes determine how these surpluses and deficits propagate through the vegetation, soil and groundwater system to streamflow. An understanding of these processes is a key component in developing and understanding the results of hydrological models (Chapter 9) and in interpreting how changing climate or land use will have an impact on the duration, frequency and magnitude of low flows. Of particular importance are soil moisture and groundwater storage, aquifer properties and the hydraulic resistance between aquifers and rivers (Figure 4.1). The continuous monitoring of catchment storages, for example, soil moisture, groundwater and lake level, provide valuable data for interpreting the results of low-flow studies (section 3.2). The key catchment processes which influence low flows are summarized below.

Precipitation input may be stored in micro-depressions; once these have been filled, water may flow to the stream as overland flow (Figure 4.1). This process tends to occur on impermeable urban surfaces and non-vegetated, sloping land with compacted topsoil or exposed rock. Overland flow rates depend on rainfall intensities and whether they exceed infiltration rates to the soil, which are lower on a clay soil than sandy soil. During freezing periods, precipitation is stored as snow and ice.

When temperatures rise above freezing, liquid water from the snow cover melts and either infiltrates into the soil or flows over frozen ground to the stream as overland flow.

As soil moisture is replenished, soil moisture content increases and water may flow vertically downward to an aquifer to recharge groundwater storage, or move laterally as throughflow towards the stream along a permeable soil layer. The available soil moisture capacity (amount of water that can be stored in the soil) may vary between a few tens to over several hundred millimetres water depth. A large soil moisture capacity provides a store to support high annual transpiration. Water can also recharge aquifers or flow laterally to the stream without fully replenishing soil moisture. This usually occurs via preferential flow paths such as cracks, macropores and pipes in the soil. In semi-arid and arid climates, a major part of aquifer recharge occurs through the river beds of ephemeral rivers. This indirect recharge often originates from high precipitation in mountainous regions upstream (see 4.2.1).

In response to recharge, aquifer storage increases as groundwater levels rise. The groundwater gradient and the transmissivity of the aquifer (saturated thickness multiplied by hydraulic conductivity) govern the groundwater discharge to the stream (Figure 4.1). If data on storativity, transmissivity or hydraulic conductivity are not available, these parameters can be estimated from hydrogeological or hydrological classifications of soils and bedrock material (WMO, 2008). When there is no recharge, groundwater discharge will continue owing to the depletion of storage. In hilly or mountainous regions, discharge from shallow aquifers of weathered hard rock often provides an important source of low flow during dry periods. In lowland areas (for example, deltas, coastal plains), deep aquifers typically exist beneath shallow aquifers, often separated by a semi-permeable layer (Figure 4.1). This may reduce storage changes and outflow characteristics of the deep aquifer. In lowland areas or large valleys, aquifers act as large storage systems and are able to feed rivers during prolonged dry conditions.

A river receives water from one or more of three different flow paths: overland flow, throughflow and groundwater discharge. Overland flow and throughflow respond quickly to rainfall or melting snow, whereas groundwater discharge responds slowly with a time lag of several days, months or years. If groundwater discharge comes from shallow saturated subsurface flow, then it responds quickly (hours or days) to rainfall or melting snow. Catchments dominated by overland flow, throughflow and/or shallow saturated subsurface flow are therefore classified as quickly responding or "flashy" catchments. Catchments fed primarily by groundwater discharge are classified as slowly responding catchments with a high base flow. Hydrograph separation techniques can be used to divide the total streamflow into a quick and a delayed component (section 5.2) The delayed flow component, commonly referred to as the base flow, represents the proportion of flow that originates from stored sources. A high base-flow proportion would imply that the catchment is able to sustain river flow during dry periods. Base-flow indices are generally highly correlated to the hydrological properties of soils and geology and the presence or absence of lakes in a catchment.

A catchment with a fast/slow response to rainfall usually has fast/slow recession behaviour (section 5.3). This is demonstrated in Figure 4.3, in which the streamflow for a quickly responding and a slowly responding catchment is shown (Tallaksen and van Lanen, 2004). Streamflow simulations were conducted for a temperate humid climate (Figures 4.3(A) and 4.3(B)) and a semi-arid climate (Figures 4.3(C) and 4.3(D)). The recharge inputs for the two different climates differ, but are similar for the two different response cases within each climate. Similarly, the aquifer characteristics of the quickly responding cases (Figures 4.3(A) and 4.3(C)) and the slowly responding cases (Figures 4.3(B) and 4.3(D)) are identical.

Low flows in the quickly responding catchments are lower than in the slowly responding ones (compare graphs 4.3(A) with 4.3(B) and 4.3(C) with 4.3(D)). For example, in the temperate, humid climate the low flows for the quickly responding catchment are regularly lower than 10 mm per month, whereas in the slowly responding catchment they are never below 15 mm/month. Low flows in the slowly responding catchments are more persistent (multi-year effects) than in the quickly responding catchments. These differences are a clear illustration of the influence of hydrological processes and storages on low flows. There is also significant climate control, with more prolonged low flows in the semi-arid climate than in the temperate, humid climate (compare graphs 4.3(A) with 4.3(C) and 4.3(B) with 4.3(D)).

Lakes and reservoirs usually have a large impact on downstream low flows. Lakes in a moist and cool

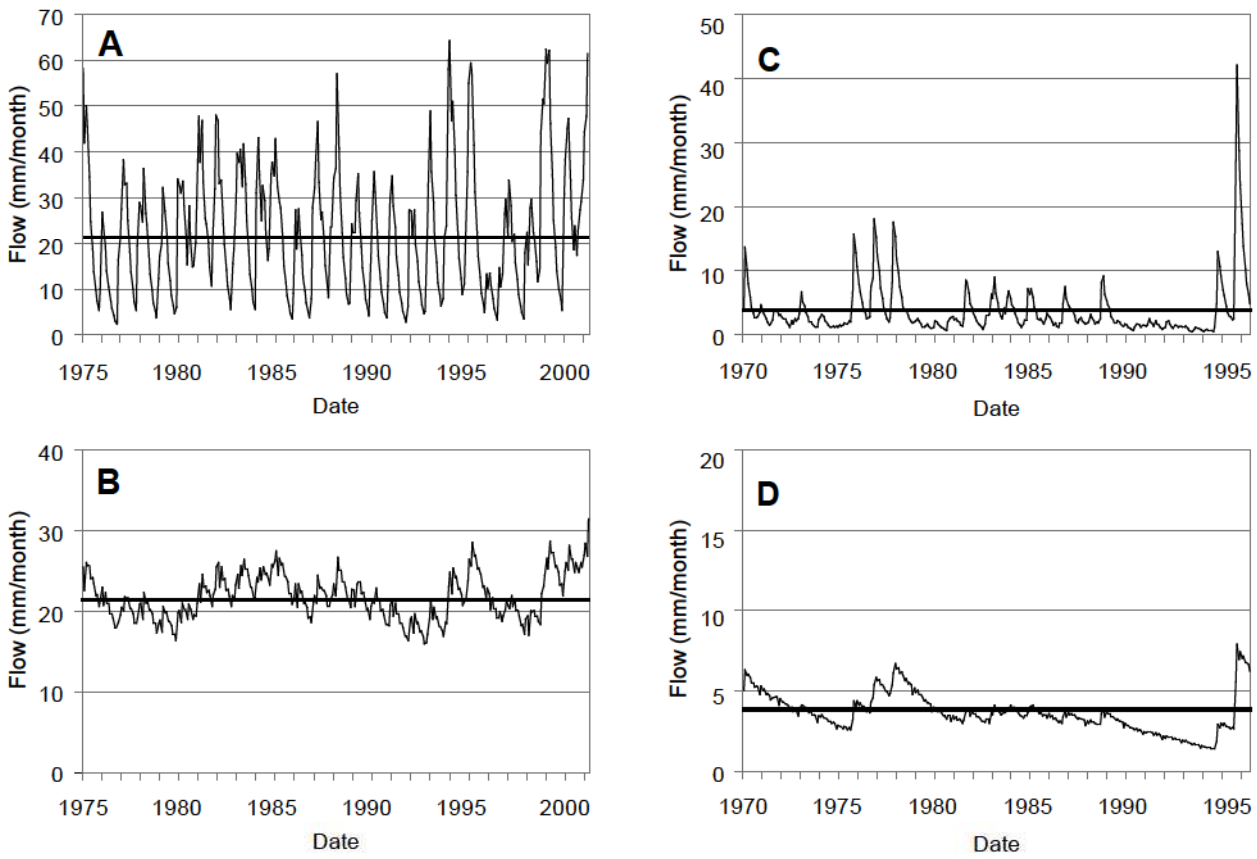

Figure 4.3 *Simulated flow to a stream in catchment: (A) temperate, humid climate and quickly responding; (B) temperate, humid climate and slowly responding; (C) semi-arid climate and quickly responding; and (D) semi-arid climate and slowly responding (straight line represents mean flow)*

climate provide additional catchment storage to maintain low flows during dry periods. In a semi-arid climate, however, downstream low flows may be smaller than those upstream of a lake due to high lake evaporation losses outweighing any increase in low flows caused by the regulatory impact. The effect of reservoirs on low flows is mainly determined by their operation and normally results in a reduction in discharge below the reservoir. Direct artificial influences on low flows are discussed in Chapter 10 and include the abstraction of water from rivers, lakes and groundwater, and the discharge of effluents into the channel. Human influences can also indirectly affect low flows through a change in land use, such as deforestation, afforestation or urbanization, and the impact of global warming on changing precipitation regimes, or that of temperature increase on deglaciation. The relationship between hydrological process and low flows and the impact of human influences on droughts are reviewed by Tallaksen and van Lanen (2004). For a comprehensive description of catchment processes, readers are referred to Dingman (2002).

4.3 Low flows in different hydrological regimes

4.3.1 Regime distinction

A monthly streamflow regime may be calculated from several years of streamflow data (section 3.3). The regime illustrates the seasonality of river flows and hence the typical duration and timing of low flows. The following sections illustrate some examples of how climate-driven seasonal hydrological regimes are modified by catchment processes. This type of analysis should be undertaken before embarking on a national or regional low-flow study to ensure that the key processes causing low flows are understood. A distinction is made between rain- and snow-dominated regimes (section 4.2). The former are further subdivided by the presence or absence of a distinct annual dry season. Glacial regimes are discussed separately.

4.3.2 Rain-dominated regimes

Climates with no distinct dry season

Rivers in tropical or temperate climates with no distinct dry season are mostly perennial, that is, they flow all year.

The seasonal distribution of rainfall will determine whether there are distinct low-flow periods. In temperate climates, the most common time for low flows to occur is towards the end of the warm season, when dry weather patterns may persist for several weeks.

Figure 4.4 shows the hydrological regimes from two small catchments in the Netherlands. The slowly responding Noor brook drains the south-eastern part of a chalk plateau and has a thick unsaturated zone and a multilayered aquifer system with substantial deep storage. Owing to these large stores, the hydrograph of the Noor does not show a strong low-flow season (see also the same watershed in Figure 4.3(B)). The quickly responding Hupsel is a catchment where a sandy shallow (2 to 8 m) aquifer overlies impermeable clay. The Hupsel hydrograph shows a more pronounced low-flow season in the summer months from May to August, when transpiration is high and storages are depleted (see also Figure 4.3(A)), and its quick response to rainfall also shows a much wider range of daily flows.

Climates with a dry season (tropical and temperate)
Rivers in all climates with a distinct dry season show a strong seasonality, with the streamflow cycle following the precipitation cycle. Amplified by high transpiration, the dry season flows are generally very low, unless the catchment has significant aquifer or lake storage. Streams draining small catchments will often be dry for pronged periods. Dry season climates are commonly similar from year to year and, as a result, the interannual variation in low-flow discharge is dependent primarily

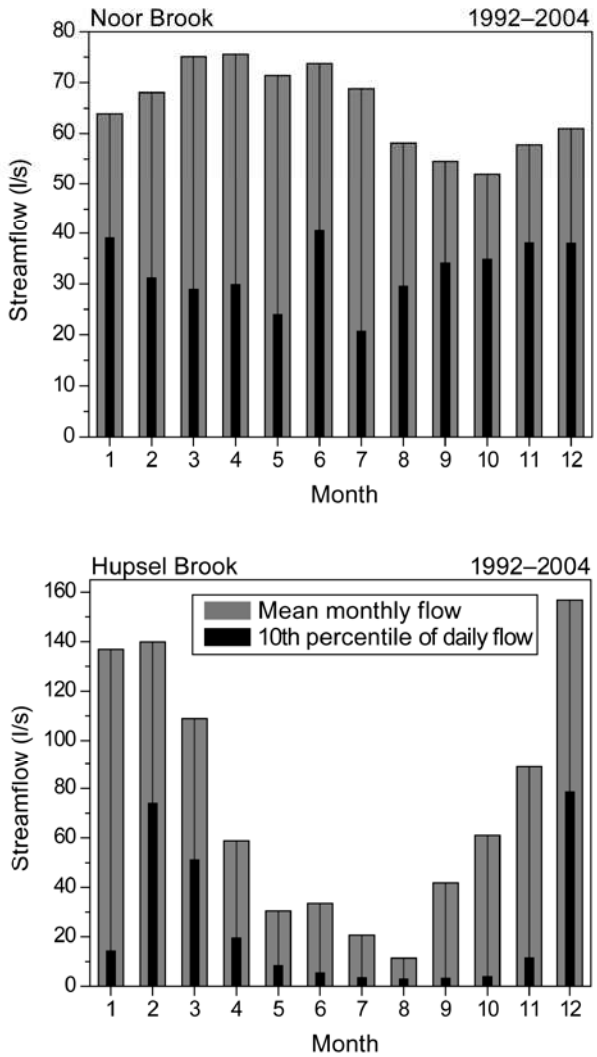

Figure 4.4 *Rain-dominated hydrological regimes in two streams in the Netherlands*

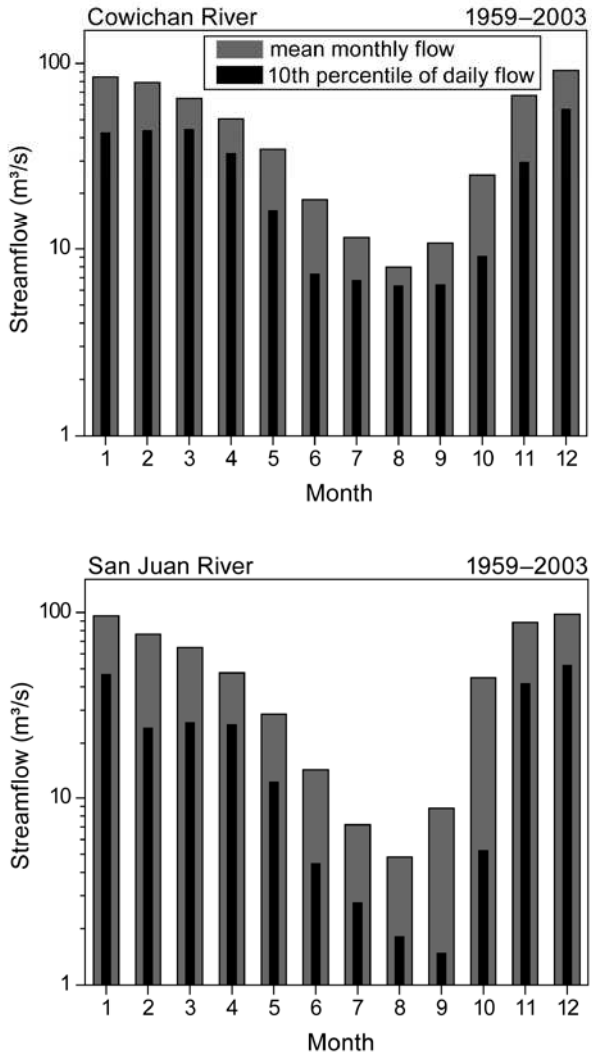

Figure 4.5 *Two rain-dominated hydrological regimes with a summer dry season in south-western Canada (Source: Water Survey of Canada)*

on the groundwater storage at the beginning of the dry season. Reservoirs (for public water supply and irrigation) are common in these regions and significantly influence downstream river flows.

Figure 4.5 shows the regimes of two rivers on Vancouver Island (British Columbia, Canada). The region has a Mediterranean climate with a dry season from June to September. Owing to the large range of flows, a logarithmic scale is used in the figure (section 3.3).

While Cowichan River (top) has a lake with a regulated outlet (during the summer months), San Juan River (bottom) has no lakes or wetlands in its catchment. Summer average and low flows in the San Juan River therefore drop to lower levels.

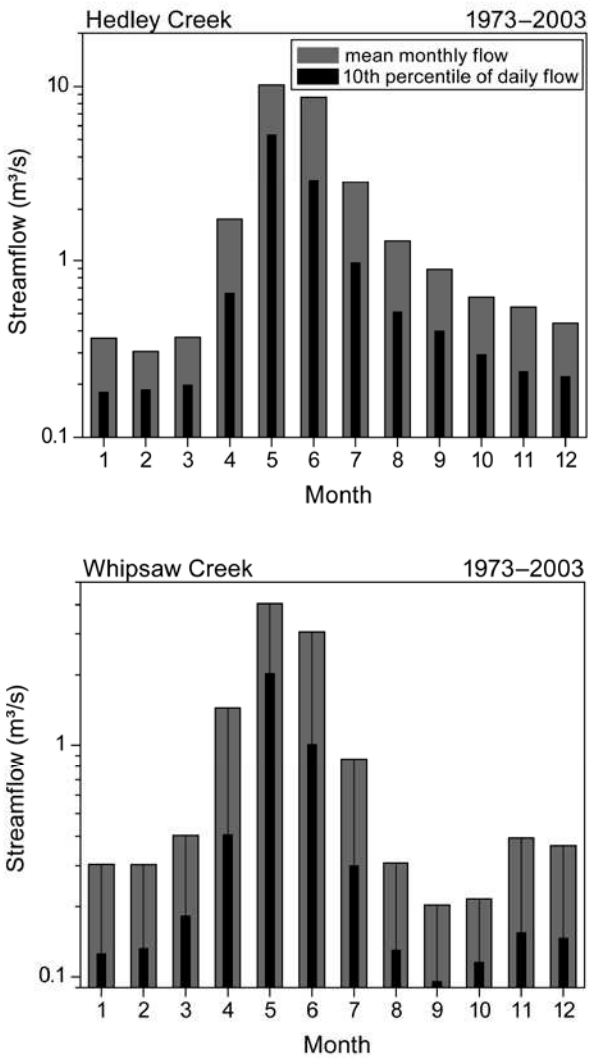

Figure 4.6 *Snow-dominated regimes in British Columbia (Source: Water Survey of Canada)*

Dry climates

Streamflow in arid and semi-arid climates is intermittent or ephemeral, that is, the rivers are dry during part or most of the year. Low-flow studies are of less relevance than understanding how occasional flood events recharge groundwater systems, how water can be conserved and in estimating reservoir yield in these systems with high interannual flow variability (McMahon and Mein, 1978).

4.3.3 Snow-dominated regimes

Snow-dominated climates are found not only at high latitudes, but also in mountain regions worldwide. They are part of the headwaters of most large river systems which eventually flow through warmer climate zones. The most important difference of snow-dominated regimes compared with rain-dominated regimes is that they do not follow the annual precipitation cycle given that precipitation is stored as snow. Low flows therefore primarily occur during the cold season (Figure 4.6). Streamflow increases with rising temperatures and increasing snowmelt. A secondary low-flow period can occur, depending on the precipitation during the warm season and the meltwater component of flow. In continental interiors and high mountains, very low temperatures during a long winter may cause soil and surface water to freeze, resulting in very low base flows. Although some water usually flows beneath river ice, in small catchments, or during extreme cold periods, streamflow may cease.

In regions with low relief, or in small mountain catchments, spring snowmelt occurs over a short period of time (days to weeks). In larger mountainous catchments, snowmelt gradually migrates from lower to higher elevations and produces a longer snowmelt period. When snowmelt ceases, streamflow recedes. The rate depends on the additional rainfall input and the storage characteristics of the catchment. In the absence of aquifer or lake storage, a second low-flow period is common.

Figure 4.6 shows examples of two snow-dominated regimes from the mountains of British Columbia in Canada. While the snowmelt peak in both creeks is very similar, the recession period in Hedley Creek (top) is slower. Hedley Creek spans a larger elevation range than Whispsaw Creek (bottom) and water is released gradually from various storages, including several small lakes in the basin's headwaters. Therefore, Hedley Creek does not show the secondary low-flow period during the summer dry season which is typical of Whipsaw Creek. Hedley Creek also maintains a somewhat higher base-flow level during the winter.

4.3.4 Glacial regimes

During the cold season and the transition season, hydrographs from glacierized catchments are similar to those of snow-dominated catchments. They are dominated by winter low flows. Spring snowmelt, however, tends to start later and lasts longer into the warm season. High elevations and extensive glaciers delay melting. The main difference between the hydrographs of glacierized and non-glacierized catchments occurs after the snow has melted. With increasing temperatures, glacier melt increases after the snow has melted from the glacier surface, while, in a non-glaciated catchment, streamflow recedes to a secondary low-flow season. This augmentation of streamflow during the warm, dry season depends on the glacier coverage in the catchment (Figure 4.7). The regime of the Blue River (top) with only 6 per cent glacier coverage strongly resembles a snow-dominated regime with a secondary summer low-flow period, while that of Canoe Creek (bottom) with 25 per cent glacier cover maintains high streamflows throughout the summer season. Streamflow in a glacierized catchment is generally less variable from year to year as it is less dependent on the annual variability of precipitation input.

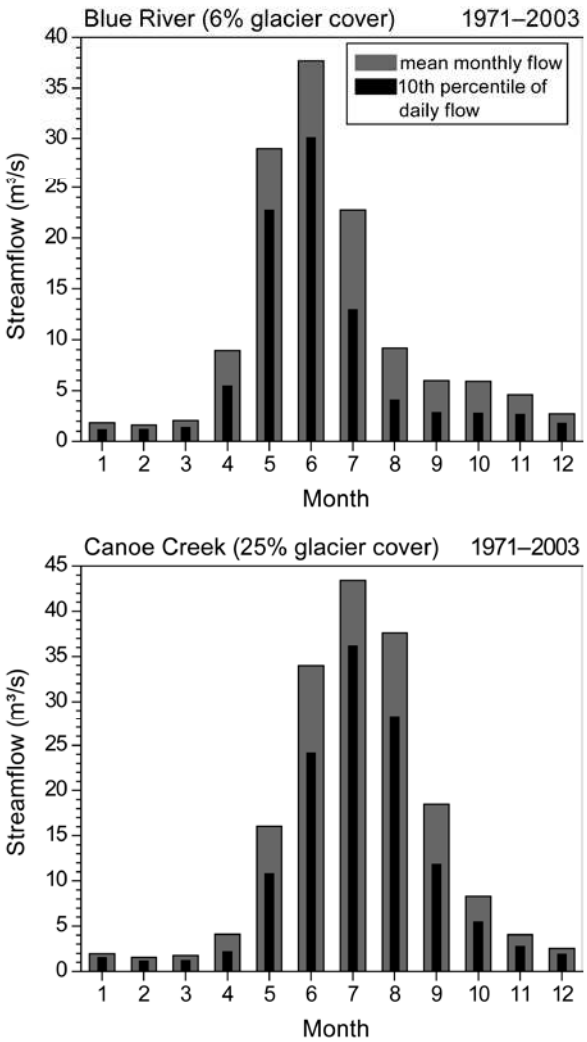

Figure 4.7 *Regimes of two glacierized rivers in British Columbia (Source: Water Survey of Canada)*

In many mountain regions of the world, low flow caused by glacial meltwater is an essential water resource. It is of particular importance in dry regions in the lee of mountain ranges (the eastern slopes of the American Cordillera), or in areas where high population density renders glacial meltwater essential (the Himalayas). Most mountain glaciers are currently receding, and this deglaciation is predicted to continue because of global warming. Depending on the climate and glacier history in a region, meltwater may increase initially as rising temperatures increase the ablation rate of a glacier. In the long term, however, the reduction in glaciated area will lead to a reduction in glacial meltwater (compare the two regimes in Figure 4.7) and hence a transition to a snow- and rain-dominated regime. This may lead to a reduction in low flows during the critical dry season.

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