SNOWSHED CONTRIBUTIONS TO THE NOOKSACK RIVER WATERSHED, NORTH CASCADES RANGE, WASHINGTON*

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ABSTRACT. Meltwater contributes to watershed hydrology by increasing summer discharge, delaying the peak spring runoff, and decreasing variability in runoff. High-elevation snowshed meltwater, including glacier-derived input, provides an estimated 26.9 percent of summer streamflow (ranging annually from 16 to 40 percent) in the Nooksack River Basin above the town of Deming, Washington, in the North Cascades Range. The Nooksack is a major spawning river for salmon and once was important for commercial, recreational, and tribal fishing, and in the past its flow met the demands of both human and aquatic ecosystems. But the river is already legally overallocated, and demand is rising in response to the rapidly growing human population. Variability in snowshed contributions to the watershed is considerable but has increased from an average of 25.2 percent in the 1940s to an average of 30.8 percent in the 1990s. Overall stream discharge shows no significant increase, suggesting that the glaciers are melting, and/or precipitation levels (or other hydrologic factors) are decreasing at about the same rate. If glaciers continue to recede, they may disappear permanently from the Cascades. If that occurs, their summer contribution to surface-water supplies will cease, and water-management policies will need drastic revision. *Keywords: environmental change, glaciers, hydrology, North Cascades Range, Washington State, water resources.*

In Whatcom County, Washington, as elsewhere in the western United States, demands on water resources are increasing. Most water-policy research concentrates on allocation and distribution, attending much less to the possible dynamics of the source regions: high-elevation snowsheds. Persons and organizations interested in agricultural, fishery, hydropower, municipal, and recreational water uses show keen interest in every drop that flows down the rivers and streams of the western United States (Rodda 1995). Indeed, in many cases, such as the Nooksack River Basin, in the northwestern corner of the North Cascades Range, Washington (Figure 1), rivers are already legally overallocated, and demand exceeds supply (Gillilan and Brown 1997; Benjamin and others 1999). More important, research suggests that snowfalls and water supplies are declining in the western United States and that they will be significantly influenced by climate changes through this century (Parson 2000).

My research determines the contribution of high-elevation snowshed meltwater to the Nooksack River watershed, a contribution previously estimated to be very large during the dry summer (Fountain and Tangborn 1985; Pelto 1993). Knowing the proportional contribution of glacier water is important, particularly because the glaciers

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are shrinking rapidly in the region (Harper 1993; Pelto 1993, 1996; Pelto and Riedel 2001). Several studies in the western United States speak to diminishing glacier size, the result of several years of negative mass balance (Marston and others 1989; McCabe and Fountain 1995; Chambers 1997). Any moisture shortage noted over glacier surfaces must also occur over nonglacierized portions of high-elevation snowsheds; links among glacier mass balance, seasonal snowpacks, water supply, and climate changes are therefore critical. If glacial recession continues at the present rate, the glaciers and their contributions to summer meltwater may be permanently lost. In that case, summer streamflows will decrease, and water-management policies within the watershed will be drastically affected (Hulme and others 1999).

The Nooksack Basin displays significant variability, including a glacierized alpine region, heavily forested mountainous uplands, and a highly developed lowland. The important role of the river system is increasingly evident as population growth, well-established agriculture and industry, a salmon population listed as a threatened species, and expanding water-based recreation and tourism stress a fully allocated surface-water supply. Determining the limits of the basin's sustainable water supply requires an understanding of the complex watershed hydroclimate.

Runoff displays significant spatial and temporal variation in the Nooksack Basin. Temporal heterogeneity arises from the intra-annual, interannual, and secular changes in temperature, precipitation, and other climatic factors (Lins 1999). Given the relatively small area of the watershed, the temporal variations generally occur in phase across the basin. Spatial heterogeneity results from the climatic, topographic, biotic, land-use, and pedologic variability within the basin. Dividing the watershed into subunits maximizes the landscape homogeneity within each area and provides a framework for analyzing runoff variations related to hydroclimatic differences between glacierized and unglacierized subbasins (Meier and Tangborn 1961). My study estimates the contribution of high-elevation snowshed meltwater to the Nooksack watershed, in the belief that knowledge of hydroclimatic variability will contribute to designing land- and water-resource-management programs that address increasing competition among users.

The Nooksack Basin

The Nooksack Basin offers an opportunity to test the hypothesis that glaciers and adjacent snowsheds in the North Cascades contribute up to 25 percent of the summer streamflow (Pelto 1993). The Nooksack River drains an area of approximately 2,015 square kilometers (Figure 1). The drainage basin is dominated by two physiographic provinces: the Puget Lowland and the western slope of the Cascades. The low-relief Puget Lowland gently rises from sea level to about 300 meters at the foothills of the Cascades. The western slope of the Cascades rises from the Puget Lowland to a series of ridges 1,000–2,000 meters in elevation, with the glacierized summits of Mount Shuksan (2,782 meters) and Mount Baker (3,284 meters) along the eastern drainage divide. Topography is of high relief, due to Pleistocene glacial erosion (Kovanen and Easterbrook 2001).

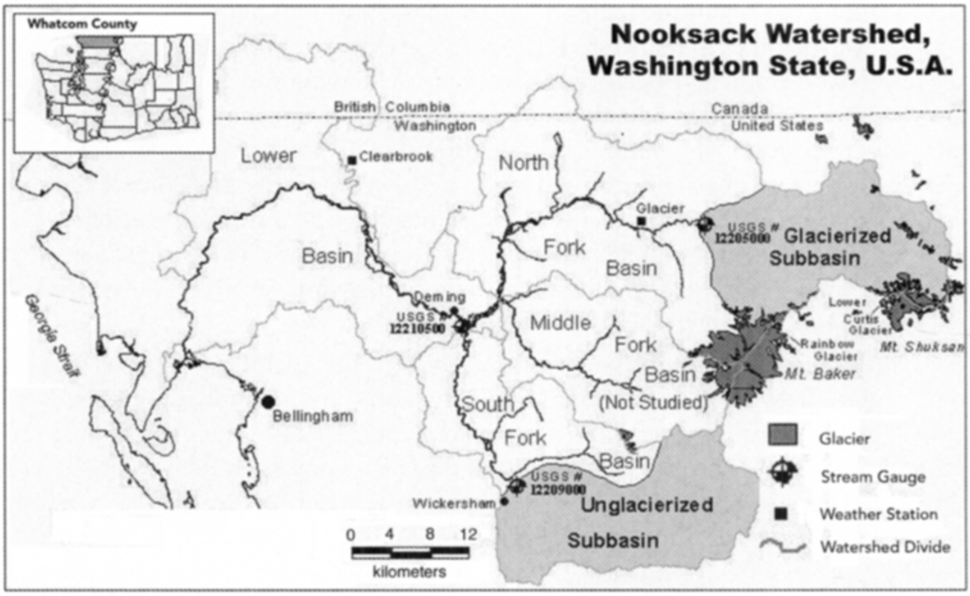

FIG. 1—The Nooksack River watershed, in the northwestern corner of the North Cascades Range, Washington. (Cartography by Eugene Hoerauf, Huxley College of the Environment, Western Washington University)

Forests dominated by fir, cedar, and hemlock covered nearly the entire Nooksack watershed prior to European settlement (Roth 1926; Omernik 1987), but they have largely been cleared for agriculture and urban development. The lower elevations of the upper basin have been logged since the 1930s.

These physiographic provinces provide two different units of land use. The Puget Lowland is drained by the lower Nooksack River, west of the town of Deming, Washington. They have been developed into intensive agriculture (irrigated field crops and dairying), and their human population of about 47,000 utilized 183.2 million liters per day of surface water from the Nooksack watershed in 1995 (USGS 2000). The upper Nooksack Basin is strikingly rural, predominantly utilized for timber harvest, wildlife habitat, and outdoor recreation and with a human population of less than 1,000. The upper basin is largely federally managed land (47 percent) at higher elevations, with private (43 percent) and state (10 percent) lands at elevations mostly below 1,000 meters. The upper basin provides an average 92 percent of the basin runoff, whereas more than 99 percent of the water use by humans takes place in the lower basin. Except for a diversionary weir for the city of Bellingham's public water supply on the Middle Fork, the upper basins contain no significant structures.

The hydroclimate of the upper Nooksack Basin is strongly influenced by a winter precipitation maximum and a steep topographic gradient from west to east that accounts for relatively abrupt changes in the quantity and form of precipitation from rain to snow. The cold, very snowy environment of the high elevations con-

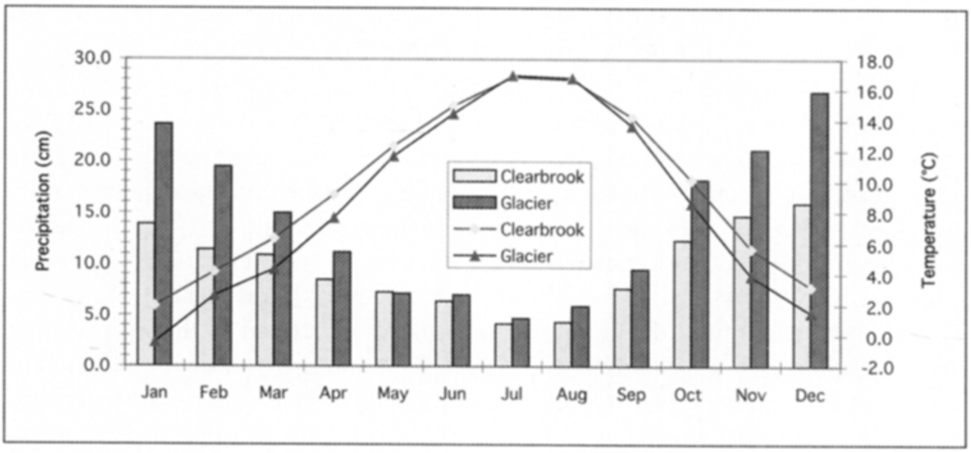

FIG. 2—Climographs for the towns of Glacier (1949–1983; elevation 285 meters; mean annual temperature 8.4°C; mean annual precipitation 1,696 millimeters) and Clearbrook, Washington (1931–1990; elevation 19 meters; mean annual temperature 9.6°C; mean annual precipitation 1,172 millimeters). *Source:* National Climatic Data Center.

trasts markedly with the mild, rainy climate of the lower elevations to the west. Mean monthly precipitation and temperature from weather stations at Clearbrook and Glacier illustrate these contrasting energy and moisture conditions in the Puget Lowland and the Cascades (Figure 2). The linear distance between these two weather stations is 31 kilometers, but Glacier is 266 meters higher in elevation than Clearbrook. Glacier's average annual temperature is 1.2°C cooler than that of Clearbrook; and it receives 52.4 centimeters more precipitation, mostly in the form of snow, than does Clearbrook.

Moisture-laden Pacific air masses generally follow a northeasterly storm track over the Puget Lowland and into the Cascades. The jet stream directs cold front after cold front through the area during the winter. Slowed by the Cascades, these storms produce low-intensity, long-duration precipitation through orographic uplift (Schermerhorn 1967). Snow levels vary throughout the winter and from year to year, but elevations above 2,000 meters commonly accumulate 8–10 meters of snow. Occasional warm southwesterly winds elevate ambient temperatures during winter storms, leading to rapid melting of snow that sharply increases runoff (rain-on-snow events). Summers are dominated by a ridge of high pressure over the Pacific, highly stable air, and low precipitation totals.

DATA COLLECTION AND METHODS

The watershed response in transforming precipitation into runoff is determined by the interaction of physiographic and hydroclimatic basin features. Two subunits were selected from within the watershed to provide a framework for analyzing runoff heterogeneity related to hydroclimatic differences between glacierized and unglacierized subbasins. Subdivision of the watershed into spatial domains expected to act independently based on the watershed's physical characteristics is recommended to improve the estimate's ability to represent runoff processes (Shelton 1989).

The downstream limit of the glacierized subbasin in the upper North Fork Basin is defined by the stream gauge near the town of Glacier (USGS Station No. 12205000), at an elevation of 380 meters (Figure 1). The 271.9-square-kilometer basin has a mean elevation of 1,311 meters, with 16.6 square kilometers (approximately 6.1 percent of its area) of glacier cover. The unglacierized basin in the upper South Fork Basin is nearly the same size (266.8 square kilometers) but much lower in mean elevation (914 meters) and relief. The highest peak in the subbasin (1,800 meters) does not support a glacier. The downstream limit of the unglacierized subbasin is defined by the stream gauge near Wickersham (USGS Station No. 12209000), at an elevation of 117 meters. The entire upper basin is represented by a stream gauge at Deming (USGS Station No. 12210500), downstream from the confluence of the subbasins and 66 kilometers above the river's mouth, at an elevation of 62 meters.

Daily discharge data from these three gauges were obtained from the U.S. Geological Survey Water Resources Division (USGS 2002). The electronically obtained data are officially listed as unverified, but no anomalous flows are apparent. All data are organized by water year (1 October–30 September) and are designated by the calendar year in which they end. Accordingly, water year 1965 began on 1 October 1964 and ended on 30 September 1965. Data from the period between 1 October 1937 and 30 September 1999 were selected for analysis based on the completeness of each record. The Deming station is missing data between 1 October 1957 and 30 September 1964. The unglacierized station is missing winter data between 1 October 1977 and 30 September 1995 but has complete data during the spring and summer months.

Descriptive statistics were calculated on daily discharge data and graphed to visualize seasonal fluctuations in each basin. Because the discharge means and standard deviations are temporally and spatially variable in magnitude, the data were standardized by calculating the coefficient of variation (the standard deviation divided by the mean) (Fountain and Tangborn 1985). Differences in daily discharge values were calculated to show which subbasin produced more discharge by subtracting the unglacierized basin discharge from the glacierized basin discharge. The two basins are roughly the same size, so differences in discharge represent heterogeneity of water inputs between them. Positive discharge values indicate that more water is produced in the glacierized basin; negative discharge values indicate that more water is produced in the unglacierized basin.

To calculate the percentage of the flow contributed to the lower Nooksack Basin by high-elevation snowshed meltwater, the difference in upper-basin discharges between the two subbasins was compared with the discharge of the total upper-basin contribution using the following equation: $\%M = (G-U)/D * 100\%$, where %M is the percentage of glacier and/or snow meltwater contributed by the glacierized subbasin; G–U is the difference in daily discharge between the glacierized (G) and unglacierized (U) subbasins; and D is the daily discharge of the Nooksack River downstream from all surface-water contributions from Cascades, measured at

Deming. Positive values of %M represent the percentage of snow and/or glacier meltwater contributed to the lower Nooksack River by the glacierized basin. Dividing the difference in discharge between the subbasins by the entire basin discharge, this estimate assumes that the variability in percentage contributions by all sources in the upper basin are the same, so that any variability in this value represents changing water contributions by the glacierized basin. Because the analyzed basin contains a fraction of the high-elevation areas of the watershed (Figure 1), these estimates are minimum values for the percentage contributions from high-elevation snowsheds in the Nooksack Basin.

Seasonal Runoff Regimes

The two subbasins exhibit annual discharge patterns that have seasonal similarities, yet important differences exist in flow characteristics within each season. Four seasonal flow regimes were identified in each basin: an autumn rainfall season, a winter snowfall season, a spring snowmelt season, and a summer low-flow (high-elevation snowshed melt) season (Figures 3–6). The homogeneity of seasonality between basins is indicative of the driving force of synoptic atmospheric conditions (Lins 1999; Peterson and others 2000). The difference in discharge within a runoff season is due to the hydroclimatic heterogeneity between the two basins.

The autumn rainfall season follows the low-precipitation–low-discharge late-summer season. Typically, discharge begins to rise in October from rain produced by midlatitude cyclonic storms. This season is typified by runoff peaks on the hydrograph resulting from the passage of each frontal system (Figure 3). The mean flow for each subbasin is between 11 and 17 cubic meters per second and gradually rises to a peak in late November as the polar front migrates into the region (Figure 4). This flow season is characterized by a high degree of variability in each basin, as indicated by the finding that the coefficient of variation nears or exceeds 1.0 (Figure 5). In addition, the coefficient of variation shows considerable day-to-day variation, thanks to the chaotic timing of precipitation and melt events. Runoff peak flows can be larger in either basin, depending on the exact path of the storm (Figure 3), but the unglacierized basin averages a higher discharge for the season. The unglacierized basin shows significantly higher variability (t-test, p >.001) as more precipitation falls in the form of rain, entering the runoff system faster than does the snow falling in the glacierized basin.

The character of the hydrographs typically changes during the month of January, signifying the change from autumn rain-dominated hydrology to winter snow-dominated hydrology. Winter typically demonstrates a decline in mean flow and runoff peak flows as precipitation accumulates in the snowpack. Both runoff peak flows and base flow decrease more in the glacierized basin than in the unglacierized basin (Figure 4). For example, the peak flow from a storm on 24 January 1998 was 64.7 cubic meters per second in the unglacierized basin but only 38.4 cubic meters per second in the glacierized basin (Figure 3). The rain in the unglacierized basin increases the relaxation time of the recession limb of the runoff peak, allowing the

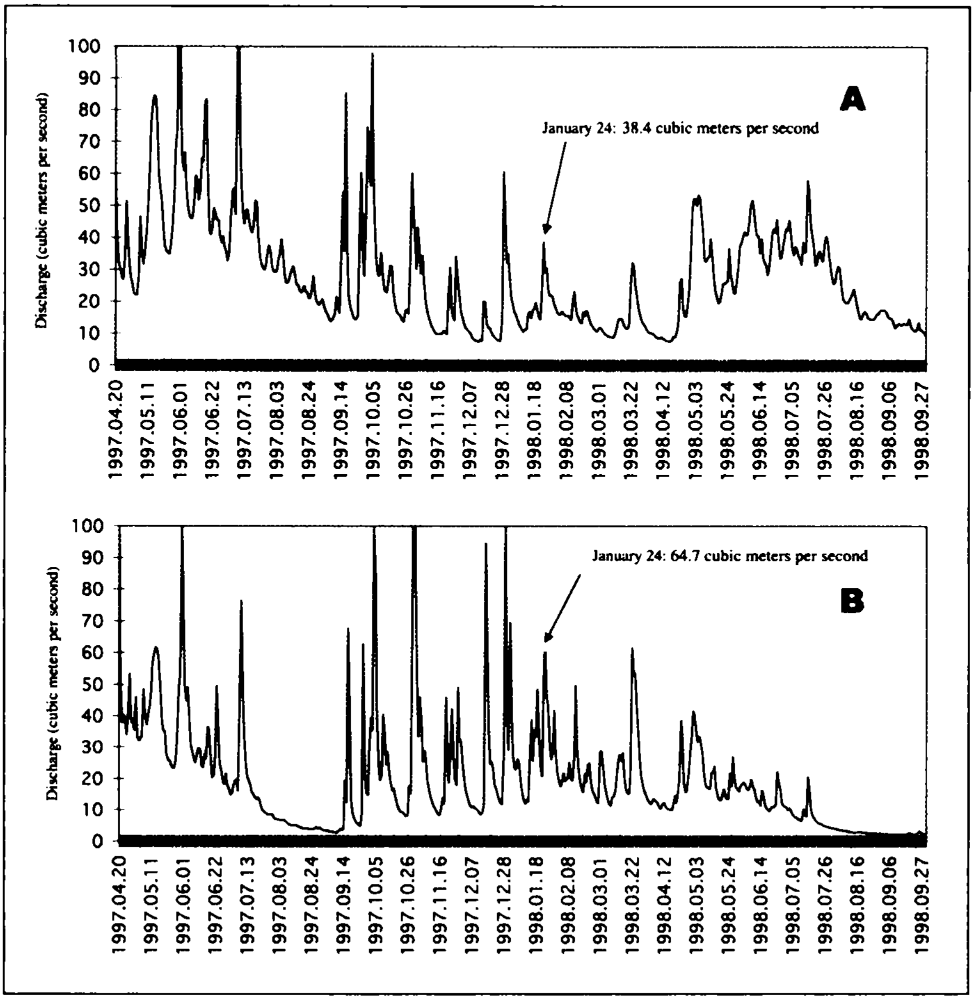

FIG. 3—Daily hydrographs from 20 April 1997 through 27 September 1998 for a glacierized subbasin in the North Fork of the Nooksack River (A) and an unglacierized subbasin in the South Fork of the Nooksack River (B). Peak flows are truncated on the graphs at 100 cubic meters per second. *Source of data:* U.S. Geological Survey.

precipitation to be converted to runoff and not allowing the flow to decline to a mean flow on the order of magnitude of earlier in the season. At the same time, the snow in the glacierized basin decreases the relaxation time of the recession limb of the runoff peak, resulting in less runoff and allowing the flow to decline to a mean flow on the order of magnitude of earlier in the season. Mean flow in the glacierized basin declines below summer flow levels, to the range of 11–17 cubic meters per second, while the unglacierized basin mean flow has dropped to 17–25 cubic meters per second (Figure 4). The coefficient of variation remains high in each basin because discharge is driven by random storm events.

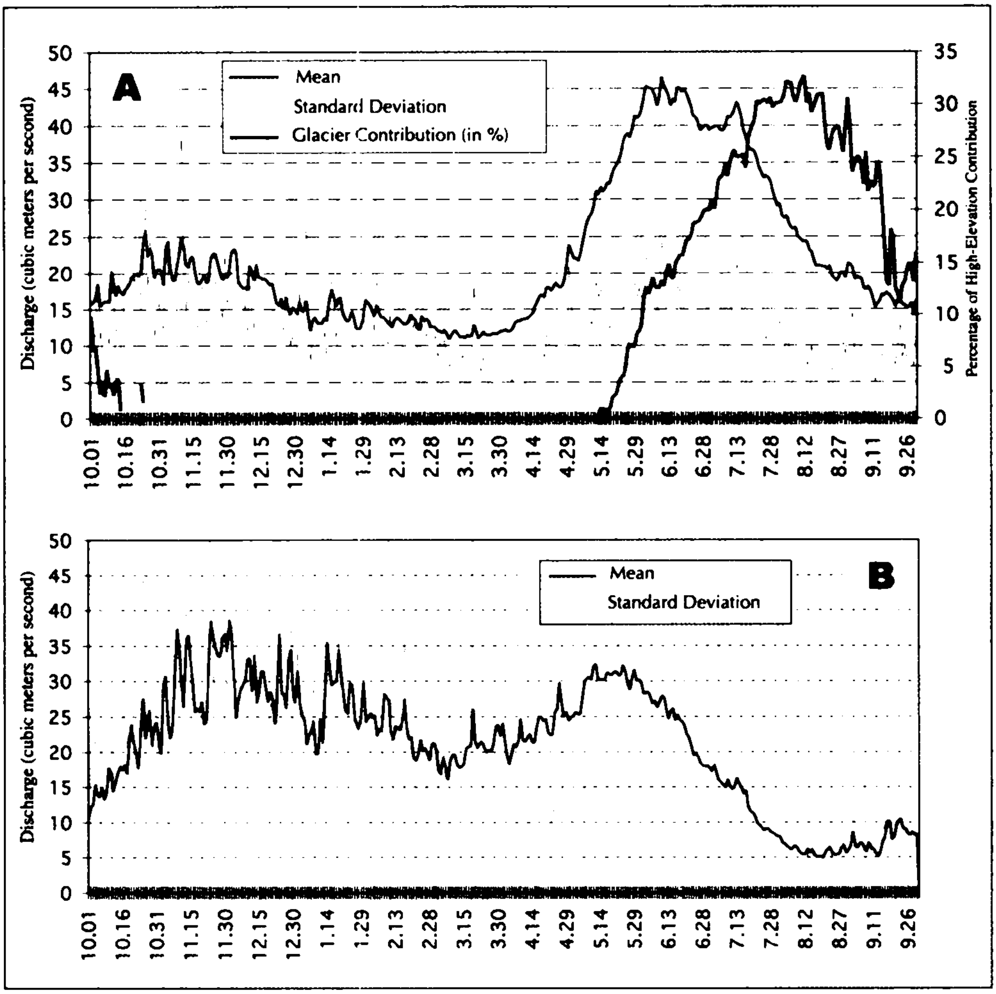

FIG. 4—Water-year hydrographs showing mean daily discharge for a glacierized subbasin in the North Fork of the Nooksack River (A) and an unglacierized subbasin in the South Fork of the Nooksack River (B). Percentages of daily discharge contributed by glacier meltwater are also shown for the glacierized subbasin. *Source of data:* U.S. Geological Survey.

The snowmelt season begins when the higher elevations start to warm up. This snowmelt may be seen in the hydrographs as a gradual rise in mean flow from March into June (Figure 4). The snowmelt is more pronounced in the higher-elevation, glacierized basin. This season corresponds with the northward movement of the polar front and the subsequent decrease in the number and intensity of precipitation events (Figure 3) and warming resulting from clearer skies. The onset of the snowmelt season begins in the glacierized basin when the mean flow rises in April or May from approximately 11 cubic meters per second and reaches a maximum during June at around 42 cubic meters per second, then gradually declines during

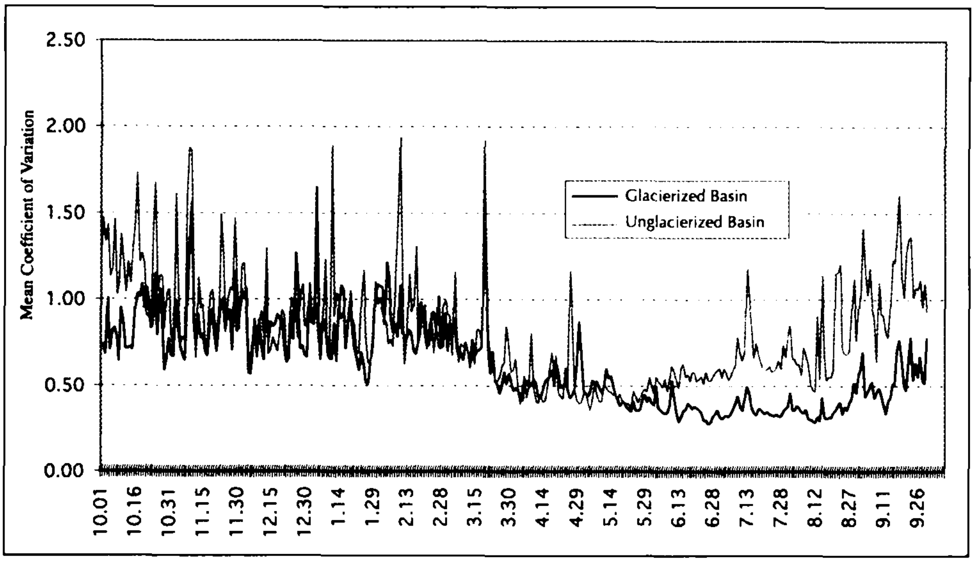

FIG. 5—Coefficients of variation of daily discharge (1937–1998) for a glacierized subbasin in the North Fork of the Nooksack River and an unglacierized subbasin in the South Fork of the Nooksack River. *Source of data:* U.S. Geological Survey.

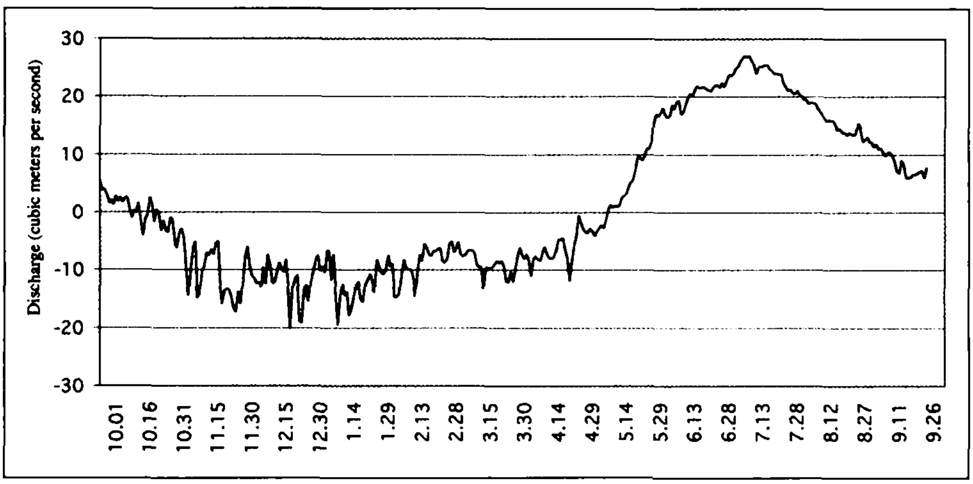

FIG. 6—Differences in average daily discharge (1937–1998) between the glacierized North Fork and unglacierized South Fork of the Nooksack River. Positive discharge values indicate that more water is contributed by the glacierized North Fork Basin; negative discharge values indicate that more water is contributed by the unglacierized South Fork Basin. *Source of data:* U.S. Geological Survey.

July. The drop in mean flow during July represents the time when the snowpack is disappearing, leaving only patches of snow and ice in high-elevation locations.

In the unglacierized basin the snowmelt season is different (Figure 4B). The snowmelt begins about two weeks earlier and reaches a peak about 70 percent the size of the glacierized basin about a month earlier (in mid-May). The decline in the snowmelt-season discharge is much faster, dropping streamflows well below the levels in the glacierized basin. The variability in daily discharge changes, from wide fluctuations around 1.0 to a stable level around 0.5, similar to the variability in the glacierized basin (Figure 5). The stabilization in variability indicates a change from storm event–dominated runoff to temperature-driven snowmelt runoff (Peterson and others 2000). A t-test (p >.001) indicates that differences in discharge between the glacierized and unglacierized basins during this season are significant. The mean flows in the glacierized are twice those in the unglacierized basin.

The summer low-flow season represents the warm, dry season of the Pacific Northwest, when the climate is dominated by the subtropical high, little precipitation falls (Figure 2), and the snowpack has largely disappeared. This hydrologic season is best illustrated in the unglacierized basin during the months of August and September, when flows drop to 6–8 cubic meters per second with few runoff peaks (Figure 3). During this season, in the unglacierized basin mean flow comes largely from groundwater discharge. The mean flow in the glacierized basin declines to 14–20 cubic meters per second but exhibits more variability. The discharge of the glacierized basin is two to four times larger than that of the unglacierized basin as a result of cooler temperatures, more surviving snowpack, and inputs from glacier meltwater. The variability in the glacierized-basin discharges during this season results from the increased melting of snow and glacier ice during warm periods, rather than from precipitation. Few precipitation-runoff peaks occur during a given year, for dry soil absorbs most of the rain.

The four seasonal runoff regimes can be seen clearly in the difference in discharge produced by the two basins (Figure 6). The autumn rainfall season is a transition between summer-flow and winter-flow regimes. The winter snowfall season is dominated by high day-to-day discharge variability. The unglacierized basin produces more runoff from precipitation in the form of rain because of its lower mean elevation; less runoff is produced in the glacierized basin, where snow is accumulating. The snowmelt season is clearly seen as the glacierized basin begins to contribute more discharge, reaching a peak in June and declining into August as the snowpack dwindles. The moderate discharge variability indicates the influence of localized rain events and warm days. The late-summer low-flow season has little variability because few storms produce precipitation and because less snow and ice are available to melt.

Total Basin Flow Contributed by High–Elevation Snowsheds

The percentage of high-elevation snowshed meltwater contributed to the lower Nooksack River from the glacierized basin is important to total basin runoff during the late spring, the summer, and the early autumn (Figures 4A and 6). Little or no high-elevation snowshed contribution is made to the main-stem Nooksack flow from the glacierized basin during the winter, and occasional contributions are made in the autumn and spring transitional seasons, when both rain and melting snow/ice are contributing to basin runoff. The rise in runoff contribution from the glacierized basin in May occurs as the lower-elevation snowpack dissipates and the snow and glacier meltwater from the higher elevations of the glacierized basin begins to contribute significantly to runoff. From mid-July through August, about 30 percent of the mean daily discharge comes from high-elevation snowshed melt. The mean high-elevation snowshed meltwater contribution for the summer discharge equates to 6.2 percent of the annual discharge.

The interannual variability in the percentage of glacier and/or snow meltwater contributed by the glacierized subbasin represents differences in snowpack accumulation and energy available in the high-elevation region. The annual contributions are normally distributed, ranging from 15.7 percent (in 1972) to 39.9 percent (in 1950) of the seasonal discharge. Interannual and secular variability in high-elevation snowshed contribution is considerable but increased from an average of 25.2 percent in the 1940s to an average of 30.8 percent in the 1990s.

High-elevation snowshed meltwater contributions reach a peak in average daily contribution of 32.7 percent on 12 August, with average daily contributions of more than 30 percent between 22 July and 20 August, a total of thirty days. Individual years show considerable variability, with contributions exceeding 30 percent occurring as early as 10 June (in 1941) and as late as 8 October (in 1999) and lasting up to 118 days in 1999 but not reaching the 30 percent level on any day in 1950 or 1956. Peak daily high-elevation snowshed meltwater contributions have been as high as 63.9 percent (on 19 July 1995) and as low as 27.9 percent (on 5 September 1955).

Evaluating Estimates

Estimating high-elevation snowshed contributions to streamflow is essential, because direct measurements from discharging glacial sources are lacking. My approach takes advantage of a unique geographical setting where discharge data from similar side-by-side glacierized and unglacierized basins can be compared. Although the approach has shortcomings—discordance between the points of discharge measurement and the high-elevation snowshed sources; poor spatial resolution (35.6 percent of basin area and 37.2 percent of basin glaciers); no records of the diurnal variability of stream discharge—my estimate improves on previous estimates by increasing temporal resolution from monthly averages to daily averages. Daily temporal resolution allows capture of significant variations that can be averaged away when using monthly discharge data. The average annual hydrographs show peaks in seasonal discharge that correspond with peak estimates based on energy (Meier 1969; Fountain and Tangborn 1985) (Figure 4).

The average estimated high-elevation snowshed meltwater contribution for the late summer (26.9 percent) agrees well with estimates of glacier meltwater contributions in the North Cascades (Pelto 1993). The estimates determined in my study represent a combination of glacier meltwater and high-elevation snowpacks, so they are maximum estimates for glacier meltwater. Studies of Mount Baker glaciers suggest that they were retreating prior to 1949, advanced between 1949 and 1978, and then began a gradual retreat (Harper 1993; Pelto 1993, 1996). The same temporal trends can be observed in the high-elevation snowshed meltwater contribution data (Figure 7). The earliest years of record have average high-elevation snowshed contributions in excess of 30 percent of the streamflow, indicative of a high ablation rate. The contribution declines into the 1940s, signifying the end of the recession period, then remains consistently low through the early 1980s while the glaciers were accumulating volume and advancing. The retreat that began in the early 1980s is clearly expressed as the meltwater contribution increases from approximately 23 percent (average, 1975–1984) to approximately 31 percent (average, 1990–1999).

Mass-balance studies have been carried out on two glaciers just outside the watershed (Pelto 1996; Pelto and Riedel 2001). The Lower Curtis Glacier is a cirque glacier on the western flank of Mount Shuksan, and the Rainbow Glacier is an outlet glacier from the Mount Baker ice cap (Figure 1). Correlations of mass-balance data between fourteen glaciers across the North Cascades indicate that the glaciers tend to fluctuate in concert with one another. The annual mass-balance measurements (1984–1998) have significant negative relationships with annual high-elevation snowshed meltwater contribution (Figure 8). The mass balance of the Lower Curtis Glacier has a stronger relationship (Pearsons $r^2 = 0.458$, $p = .0056$) than does that of the Rainbow Glacier ($r^2 = 0.315$, $p = .0296$). This expected negative relationship suggests that the estimate represents, to some degree, high-elevation snowshed meltwater contributions to the watershed.

Impacts of High-Elevation Snowshed Meltwater on Annual Hydrology

High-elevation snowshed meltwater has five principal impacts on watershed hydrology: lower stream temperatures; sudden, unexpected contributions to discharge caused by glacial reservoir outbursts; increased summer discharges; temporal delays in maximum spring discharges; and decreased annual, especially summer, variations in runoff (Fountain and Tangborn 1985). My study did not address stream temperature or glacial outbursts, but the summer increase in discharge, delay of spring peak discharge, and decrease in runoff variability were detected.

The mean high-elevation snowshed meltwater contribution in the Nooksack Basin for the summer discharge was estimated to be 26.9 percent. During the summer the glacierized basin produces about three times the amount of streamflow as does the unglacierized basin (Table I; Figure 4). This quantity of water may not seem overly important, but summers are dry and streams run low while human demand increases dramatically. In the absence of high-elevation snowsheds and glaciers, the summer discharge of the lower Nooksack River would drop, resembling the hydrograph of the unglacierized basin.

Maximum spring runoff occurs an average of twenty-nine days later in the glacierized basin than in the unglacierized basin, whereas its snowmelt season only starts seven days later (Figure 4). The delay in high-elevation snowshed melt is due to a slow rate of warming at higher elevations and to a larger volume of snow to melt. The quantity of meltwater in the unglacierized basin is limited by the snowpack volume, but the glacierized basin has a meltwater source that is limited only by the energy required for melting (Fountain and Tangborn 1985). The low-elevation snowpack generally disappears from the North Cascades by late June. The glaciers, however, continue to melt at an increasing rate as temperature, solar radiation, cloud cover, and snow-ice albedo factors combine for effective ablation through August (Meier 1969).

The coefficient of variation of daily discharge is significantly (t-tests, $p > .001$) smaller during all seasons except winter and annually in the glacierized basin than in the unglacierized basin (Tables I and II; Figure 5). The lower coefficient of variation during the autumn is due to more precipitation accumulating as snow in the glacierized basin than the unglacierized basin, as well as to extended snowmelt during warm years. The coefficient of variation converges between the two basins in winter as snowfall becomes the mode of precipitation. Both basins experience a significant drop in the coefficient of variation during the spring snowmelt as precipitation inputs to streamflow become less important. Although significantly higher in value, the spring unglacierized-basin coefficient of variation is reduced by the snowmelt, causing basin variability to behave in a glacier-like manner.

The greatest difference between the two basins is in summer (Table I). The glacierized-basin discharge is fairly consistent from day to day, fluctuating largely in response to temperature and solar radiation, which melt the snow and glacial ice. Precipitation events produce only modest increases (if any) in discharge because the accompanying cloud cover reduces melting and because the dry soil absorbs most of the rainfall. In the low-flowing, unglacierized basin the same precipitation event produces a much larger runoff.

The dimensionless coefficients of variation allows comparisons to be made between watersheds of different sizes. The coefficient of variation for the entire upper Nooksack Basin (Deming station) is not significantly different (t-test, $p > .001$) from that for the glacierized subbasin on an annual or seasonal basis, except in winter (Tables I and II). The coefficient of variation for the unglacierized subbasin is always significantly larger than the Deming coefficient of variation, however. Even though glaciers constitute only a small portion of the entire watershed, hydrologic processes associated with them have a distinct imprint on the downstream watershed, buffering daily variations in flow. The high-elevation snowshed meltwater contributions in summer and the accumulation of snow in high elevations of the basin reduce the variability of the surface runoff within the entire watershed.

My analysis of coefficients of variation appears to be at odds with the analysis of Andrew Fountain and Wendell Tangborn (1985), who found low a coefficient of variation in the winter and a high coefficient of variation in the summer. The differ-

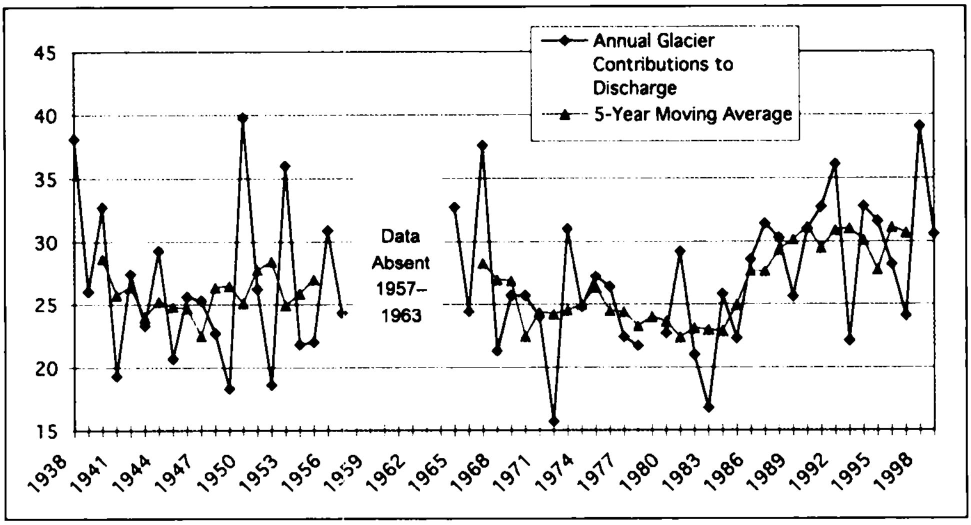

FIG. 7—Percentages of annual high-elevation snowshed meltwater contributions to the lower Nooksack River Basin during the melt season, 1938–1956 and 1964–1999. A five-year moving average is also shown. *Source of data:* U.S. Geological Survey.

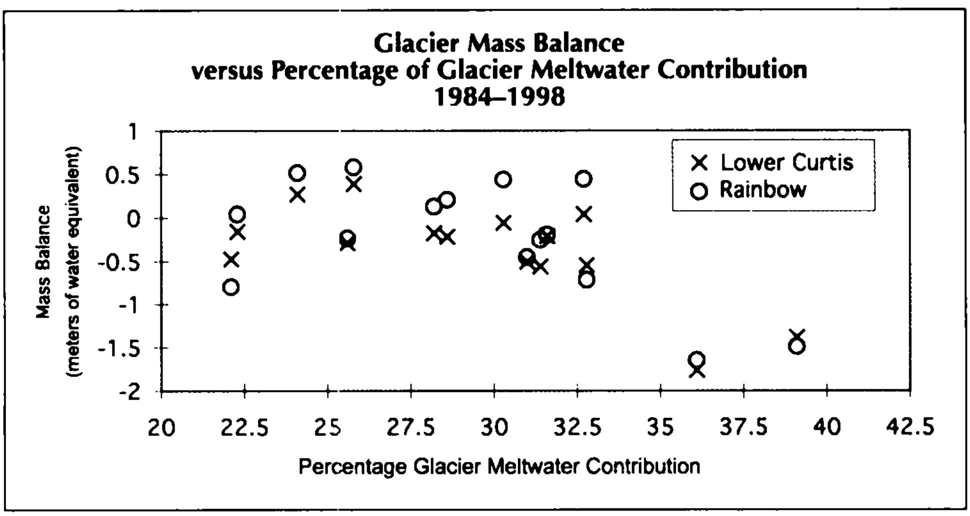

FIG. 8—Scatterplot of mass-balance data for Lower Curtis and Rainbow Glaciers versus percentages of glacier meltwater contribution for the entire basin. *Source:* Pelto and Riedel 2001.

ence stems from timing of the sampling: My study uses daily discharge data, whereas Fountain and Tangborn use monthly data. On a monthly basis, autumn and winter months do not exhibit much interannual variation (that is, rainfall is always abundant), whereas individual days show a tremendous variability (for example, no rain one year, but 5 centimeters the next). On a monthly basis, summer months exhibit

Table I—Hydrologic–Season Data for Basins in the Study Area, Nooksack River Watershed, Whatcom County, Washington[a]

Basin	Average Starting Date	Average Length	Average Daily Discharge[b]	Coefficient of Variation
Autumn Precipitation Season				
Glacierized subbasin	10 October ± 16 days	105 ± 43 days	21.1 ± 6.1	0.86
Unglacierized subbasin	5 October ± 19 days	140 ± 39 days	28.1 ± 5.5	1.00
Entire upper basin (Deming)	3 October ± 22 days	139 ± 36 days	110.7 ± 23.7	0.83
Winter Precipitation Season				
Glacierized subbasin	23 January ± 40 days	57 ± 33 days	9.7 ± 3.1	0.81
Unglacierized subbasin	22 February ± 37 days	22 ± 30 days	13.4 ± 6.7	0.80
Entire upper basin (Deming)	20 February ± 32 days	20 ± 16 days	53.7 ± 13.6	0.68
Snowmelt Season				
Glacierized subbasin	20 March ± 26 days	111 ± 31 days	30.7 ± 6.4	0.45
Unglacierized subbasin	13 March ± 22 days	110 ± 28 days	29.5 ± 5.0	0.55
Entire upper basin (Deming)	11 March ± 28 days	129 ± 31 days	111.6 ± 22.7	0.45
Glacier-Melt Season				
Glacierized subbasin	8 July ± 16 days	93 ± 21 days	21.3 ± 5.4	0.46
Unglacierized subbasin	3 July ± 19 days	95 ± 25 days	6.6 ± 1.8	0.86
Entire upper basin (Deming)	18 July ± 15 days	77 ± 25 days	48.8 ± 11.0	0.50

[a] All ranges ± 1 standard deviation.

[b] Discharge in cubic meters per second.

TABLE II—BASINS IN THE STUDY AREA, NOOKSACK RIVER WATERSHED, WHATCOM COUNTY, WASHINGTON

BASIN	USGS STATION NUMBER	PERIOD OF RECORD	DISTANCE FROM RIVER MOUTH (km)	STATION ELEVATION (m)	WATERSHED AREA (km^2)	MEAN ANNUAL DISCHARGE[a]	COEFFICIENT OF VARIATION	AVERAGE WATERSHED ELEVATION (m)
Glacierized subbasin	12205000	1938–1999	93	380	271.9	22.0 ± 9.9	0.63	1,311
Unglacierized subbasin	12209000	1938–1999[b]	83	117	266.8	20.8 ± 8.6	0.82	914
Entire upper basin (Deming)	12210500	1938–1957, 1964–1999	66	62	1,512.6	94.0 ± 25.9	0.62	1,142

[a] Discharge in cubic meters per second; range ± 1 standard deviation.
[b] Winter data for 1978 through 1994 missing.

considerable interannual variation, whereas individual days show less variability (that is, mostly with no rainfall). Ignoring the differences in magnitude, seasonal trends in the coefficient of variation are consistent.

Interannual variations in high-elevation snowshed meltwater are a product of seasonal temperature and precipitation regimes, glacier mass balance, and the health and size of glaciers (Fountain and Tangborn 1985). Alpine-glacier mass balance is quite sensitive to changes in synoptic climatology: Any meteorological processes operating over glacier surfaces must also occur over nonglacierized portions of high-elevation snowsheds (Barry 1990). In other words, when the snowpack is abundant or the temperatures are cold, less high-elevation snowshed meltwater is contributed to runoff, whereas during drought or warm years high-elevation snowshed meltwater augments streamflow. The net effect of the hydrologic impacts of high-elevation snowsheds is to buffer the year-to-year variation in streamflow caused by the variations in precipitation (Meier and Tangborn 1961). Glacierized basins will produce more meltwater in dry or warm years than in wet or cool years, thus reducing the interannual fluctuations in discharge.

Possible Effects of Climatic Changes

Glacier environments are especially sensitive to climate changes and variability (Barry 1990). Several climate models agree that the Pacific Northwest will probably experience a 1.7–2.8°C temperature increase and a 1–10-centimeter increase in winter precipitation during the early twenty-first century (Parson 2000). As a result, runoff characteristics may change appreciably over the next several decades. In the near term the effects of global warming are likely to be masked by ongoing year-to-year climatic variability (Trenberth 1999). The relatively low elevation of much of the surface area of the North Cascades glaciers could cause their retreat and demise during this century.

Higher temperatures will probably both cause a higher percentage of annual precipitation to fall as rain (that is, higher snow lines) and accelerate summer ablation (Pelto 1996). As glacier recession accelerates, summer runoff is likely to increase. The trend seen in the Nooksack data over the last sixty years, where the contribution by the high-elevation snowshed has increased from approximately 25 percent to approximately 30 percent, will probably continue (Figure 7). After the glaciers have largely melted away, their input will be lost, resulting in a reduction in flow by 25–30 percent. This reduction in stream discharge is likely to occur within a few years near the end of a glacier's life.

Though not currently predicted, the climate of the North Cascades could become less conducive to high-elevation snowshed meltwater, a fear also expressed for other parts of the Cascades and even for the Sierra Nevada of California and Nevada. If annual or seasonal temperatures fall, snow and ice melting and, therefore, summer streamflows will decline. If snowfall increases, the high-elevation snowshed meltwater contribution will decrease because the glaciers will remain under snow cover for longer periods in summer. An increased snowpack will lead to an increase in summer streamflows, however, because more snow will be available to melt. As discussed above, the high-elevation snowshed meltwater contribution to the flow of the Nooksack River has fluctuated through time but appears to have increased in response to warming during the late twentieth century (Figure 7).

Regardless of climate changes, streamflow regimes and glacier mass balances in the Pacific Northwest are prone to interannual and secular variations related to large-scale patterns of climate variations over the Pacific, the El Niño–Southern Oscillation and the Pacific Decadal Oscillation (McCabe and Fountain 1995; Nigam, Barlow, and Berbery 1999; Parson 2000). The predominant pattern is that warm years tend to be relatively dry, with light snowpacks, lower spring streamflows, and higher summer streamflows, whereas cool years tend to be relatively wet, with heavy snowpacks and high streamflows. Warmer years tend to see water shortages, increased glacier melt, and less-abundant salmon runs (Pelto 1996; Mantua and others 1997; Hulme and others 1999). The Pacific Decadal Oscillation has been in the warm, dry phase since 1977 but appears to be moving toward the cool, wet phase (Nigam, Barlow, and Berbery 1999). Global warming is likely to increase the frequency and magnitude of these climatic variations and their impacts on the hydrological system (Trenberth 1999).

Implications for Water Resources

The high-elevation snowsheds in the Nooksack River watershed have a significant impact on downstream hydrology. Although the influences of high-elevation snowshed meltwater fluctuate from year to year with meteorological conditions and trends, the hydrology of the Nooksack Basin strongly reflects glacial conditions. Water users in the basin, including its ecosystems, rely on the seasonal patterns and expected range of variation in surface runoff produced by the glacierized watershed. Two modes of change are at work within this watershed, however. Rapid population growth and rising environmental concerns are increasing demand for water. Climate change and variability appear to be augmenting the surface supply by melting glaciers, so the higher rates of flow evinced in glacier-fed basins are artificially and unsustainably high; when the glaciers go, so will the water supply. If current climate trends continue, when the glacier mass has entirely melted, the shortfall in the overappropriated basin hydrology will be significant. A new hydrologic regime will be in place: 25–30 percent less summer flow, spring runoff peaks earlier in the year, and increased variability in streamflow, including larger storm-peak flows.

Rapid population growth, increasing environmental concerns, and resulting changes in the character of water demands have led to increased competition for water even under normal flow conditions (Gillilan and Brown 1997). Western water-management practices, storage infrastructure, and patterns of use are tuned to the expected range of variation in surface runoff and groundwater availability. The abundant surface-water supply in the upper Nooksack Basin has promoted a historic reliance on this resource throughout the entire basin. Growing human and environmental demands on water quantity and quality require comprehensive water-development strategies that incorporate the relationship between lowland and upper watershed supplies. My study suggests that late-summer surface supplies are derived, in part, from a limited source: glaciers. Because glacier volume and high-elevation snowfall respond to climate change and variability, the input from these sources is likely to change during this century.

The Nooksack River supplies drinking water, hydroelectric power, recreation, fisheries habitat, irrigation water, and water for several industries in the region (Benjamin and others 1999). Demands increase substantially during the summer. Were water supplies to reduced by 20–30 percent, the system would further tax the slim margins on which it operates today. Water withdrawals for human use would need to be reduced, resulting in economic hardships in the agricultural, industrial, and eventually service sectors (Rodda 1995). Indeed, this scenario was witnessed in California in the late 1980s and early 1990s following multiple years of drought (Harding, Sangoyomi, and Payton 1995).

Fish populations and other aquatic resources are affected by changes in seasonal flow regimes, total flows, warmer water temperatures, and associated changes in water quality (Mantua and others 1997). Changes affect the health of aquatic ecosystems, with impacts on spawning practices, productivity, species diversity, and species distribution. Salmon populations rely on the Nooksack River for various distinct habitat requirements during different stages of their life cycles (Myers and others 1998). Hydrologic changes to their riverine habitat may further negatively affect their already severely depressed populations (Miller 2000).

Clearly, high-elevation snowsheds are important to the regional water supply. Recognizing and predicting further changes in water supply will help water managers provide water to the growing population of the region while protecting already heavily impacted aquatic ecosystems. New reservoirs and water-transfer systems require considerable lead time to plan and construct. Such structures may be needed to deal with declining water supplies in this part of Washington. It is critical that we understand how water is supplied today so we can manage the resources under different climatic conditions that may exist in the future.

These changes will have an impact all water users in the basin. New allocation and distribution systems are required to meet the new water regime. Additional flood controls and storage facilities may be required if variability in flow increases. Hydroclimatic variability represents a major challenge for land and water-resource development in the watershed. My study increased our understanding of how high-elevation regions influence a lowland water supply. Effective water-development planning and policymaking must recognize how changes in upper-watershed conditions will affect water resources.

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