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Reconstructed Runoff from the High Arctic Basin Bayelva based on Mass-Balance Measurements

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The river Bayelva drains a catchment area of 31.5 km^2 in the Kongsfjord area close to the research station Ny-Ålesund (79° N 12°E) on the northwest coast of Spitsbergen. The basin is 54% glacierized, and the studied glacier Austre Brøggerbreen is 6.1 km^2 and constitutes 20% of the basin. On this glacier a mass-balance monitoring program including accumulation and ablation measurements has been carried out continuously since 1967. The winter snow accumulation shows very stable conditions with a mean accumulation of 0.71 ± 0.16 m/year in water equivalent. The runoff from the glacier in an equilibrium year should thus be 4.33×10^6 m^3. The mean ablation on this glacier has been greater than the winter accumulation, 1.14 ± 0.26 m/year of water equivalent, which results in an annual runoff of 6.95×10^6 m^3. That is more than 60% higher runoff from the glacier than in a year with zero net balance. The result is a mean net balance of – 0.42 m/year, or an annual runoff from the glacier due to the retreat of the glacier of 2.6×10^6 m^3.

In Bayelva, a runoff station was operated from 1974-1978. In 1988 this basin was chosen as a hydrological research site, and the runoff measurements were restarted and a permanent station for water discharge and sediment transport measurements was constructed in the river. This basin is the only one in Svalbard with some years of hydrological data. The water balance discussion shows that there is good agreement between the measured runoff in the river Bayelva and the potential runoff calculated from the mass-balance measurements on Brøggerbreen. On the basis of this correlation the total annual runoff was reconstructed from the whole period of mass-balance data from 1967-1991. The runoff from the whole basin has been 30% higher than in years with an equilibrium mass-balance on the glacier.

Introduction

At high latitudes in the Arctic, glaciers and snow-covered areas play an important role in the hydrological cycle. Most of the potential runoff is stored in solid form as snow or ice. In Svalbard, glacier mass-balance studies have been carried out on some selected glaciers since 1950. On Brøggerbreen (78° 53' N), on the north west coast of Spitsbergen a mass-balance monitoring program including accumulation and ablation measurements has been carried out continuously since 1967 (Hagen and Liestøl 1990).

The aim of this paper is to discuss runoff contribution sources, reconstruct the runoff in the river Bayelva, and discuss the water balance in the basin using the mass-balance results from Austre Brøggerbreen. The calculated runoff is compared to actual water discharge measured during some years of monitoring.

A major problem in flow monitoring in Svalbard is the lack of stable channels. Usually the rivers drain in numerous braided streams. In Bayelva, however, the braided river on the sandur area is routed through a well defined rock channel, suitable for a gauging station, before it drains into the sea. Hydrological monitoring was carried out in Bayelva during the period 1974 to 1978 (Repp 1979, 1988). In this period a natural profile in the river was used. There are always problems with superimposed ice in the spring and the formation of bottom ice in the river, especially at the beginning of the melt season. In order to try to minimize this difficult period, it was decided to build a permanent compound crump weir with a known rating curve. The monitoring station was constructed in 1988/89 and has been operating since then. Technical problems with leakage under the construction gave unreliable data in 1989 and at the end of the 1990 season.

Hydrological data from Arctic regions are sparse. In Svalbard some hydrological investigations have been carried out by Russian scientists (Gokhman and Khodakov 1986) and Polish scientists (Pulina *et al.* 1984).

The Basin

The basin is in the Kongsfjord area close to the research station Ny-Ålesund (79° N 12°E) on the northwest coast of Spitsbergen. The river Bayelva drains a catchment area of 31.5 km^2 (Fig. 1). The basin is well defined in typical cirques formed by glacier erosion. The glaciers Vestre (Western) and Austre(Eastern) Brøggerbre cover the main part of the basin, a total of of 54% or 17.1 km^2. The glaciers are surrounded by steep mountain ridges. Thus the non-glacierized portion of the basin is partly free of snow during the whole year. In front of the glaciers are ice-cored moraines and a sandur area.

The climate is strongly influenced by the North Atlantic Current resulting in a rather maritime climate on the west coast of Spitsbergen. Annual precipitation rang-

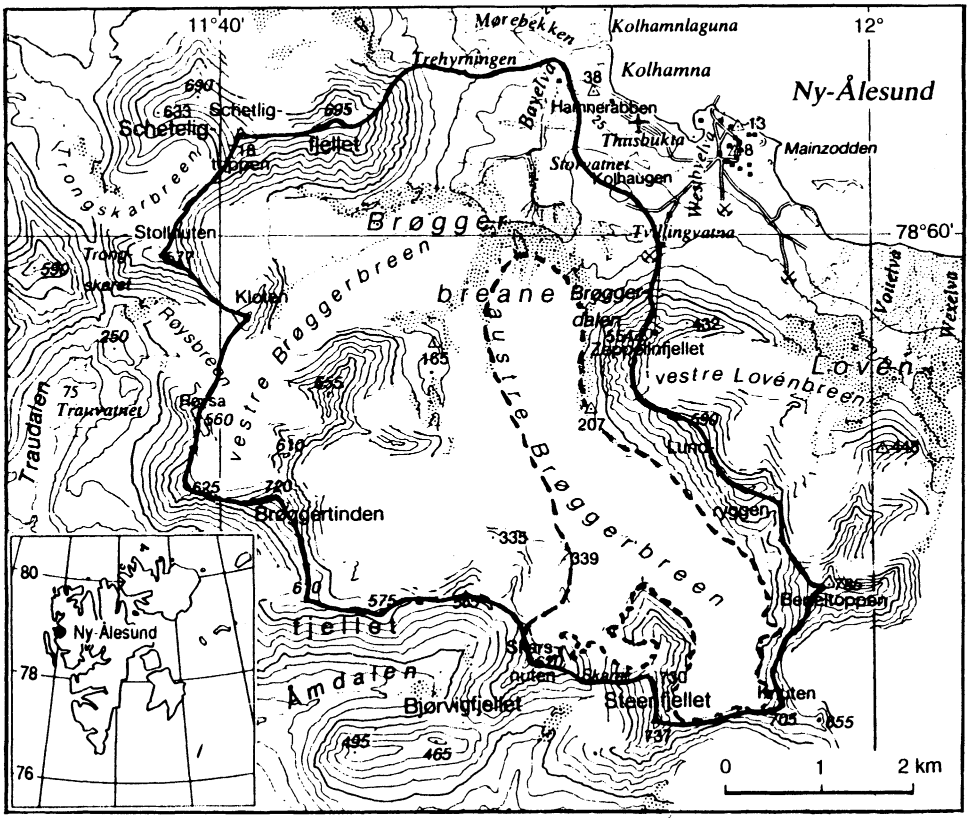

Fig. 1. Bayelva basin and the location in Svalbard.

es usually from about 400 mm/year in the lowland up to about 1,000 mm/year in the higher areas. In Ny-Ålesund the mean annual precipitation in 1975-1989 was 372 mm, and the annual average temperature was – 6.2°C (Hanssen-Bauer *et al.* 1990). The summer months have mean temperatures above zero (June 1.5°C, July 5.0°C, August 3.9°C and September-0.5°C). Even the highest areas of the glaciers at about 800-1000 m a.s.l. usually have some days with temperatures above zero and surface snow melting. Svalbard is within the continous permafrost zone with permafrost thickness varying from 100 m near the coast up to 500 m in the high mountains (Liestøl 1977). However, the glaciers are mainly of the subpolar, or polythermal, type, *i.e.*, with cold and temperate parts. The occurrence of meltwater soaking and refreezing in the thick snow/firn layers in the accumulation area raises the temperature to zero. Thus, taliks can be found in and under most glaciers in Svalbard. In the ablation area most of the water drains off at the surface. Therefore, the refreezing mechanism is less effective there.

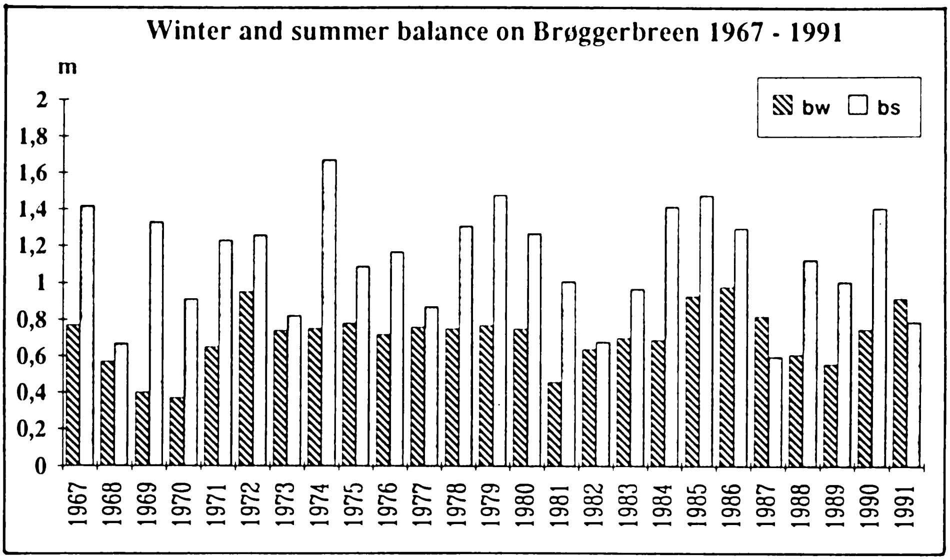

Fig. 2. Annual mass-balance data showing winter and summer balance for 1967-1991.

Mass-Balance Data

Snow Accumulation

Reliable spot measurements of precipitation are difficult because most of it comes in connection with strong winds and snow drift. In Ny-Ålesund the meteorological station is situated only 5-6 km from the central areas of the glaciers. However, the correlation between the measured winter precipitation from September to June at the station and the snow accumulation measured by sounding profiles over the entire glacier surface is not high. During the 14-year period 1974-75 to 1987-88 the correlation coefficient was 0.63 (Hagen and Liestøl 1990).

The mean winter accumulation on Brøggerbreen during the period 1967-91 is 0.72 ± 0.16 m in water equivalent. As can be seen in Fig. 2 the annual variations are fairly small. The altitudinal increase of snow accumulation has a fairly constant gradient db_w/dz = 1 kg $m^{-2}m^{-1}$, or 100 mm/100m.

Trend analysis of the measured winter balance shows a slight increase of the winter accumulation through this period.

Summer Ablation

During the observation period (1967-91) the mean summer balance has been 1.14 ± 0.29 m water equivalent on Brøggerbreen. Ablation values show more fluctuations than the winter balance values (Fig. 2). Summer balance (b_s in m y^{-1} water equivalent) as a function of positive degree days (PDD), the cumulative sum of daily temperatures above freezing mean temperature for the whole summer season, gives a high correlation coefficient and the following regression equation (Hagen and Liestøl 1990)

$$b_s = 0.0046\ PDD_{6-9} - 0.6259 \quad \text{with} \quad r = 0.88 \tag{1}$$

There is no sign of increased melting. The trend for the whole period is rather the opposite with a very slight negative trend of the cumulative PDD.

Net Balance

The glaciers are not in balance with the existing climate since the summer ablation has been greater than the winter accumulation in nearly all observed years, resulting in steadily decreasing ice masses. The mean annual specific net mass-balance is -0.42 m water equivalent (Hagen and Liestøl 1990). Cumulative net balance is shown in Fig. 3 which shows reconstructed net balance since 1912 together with the measured period 1967-1988 (Lefauconnier and Hagen 1990). The total mass lost between the balance years 1967/68 to 1990/91 was 54.6 × 10^6 m^3, which corresponds to an average lowering of the glacier surface of 9.9 m. That is more than 10% of the total volume of the glacier.

Only two balance years, 1986-87 and 1990/91, had positive net balances during these twenty-five years, respectively + 0.22 m and + 0.13 m, mainly due to cold summers with less melting than in an average year.

The net balance decreased slightly from 1967 to 1988. Thus the potential extra runoff due to retreat of the glacier also decreased slightly. The reason for this is partly due to slightly decreasing summer balance, but also due to a decrease in the area of lower altitudes of the glacier. The front is retreating and the surface lowers both

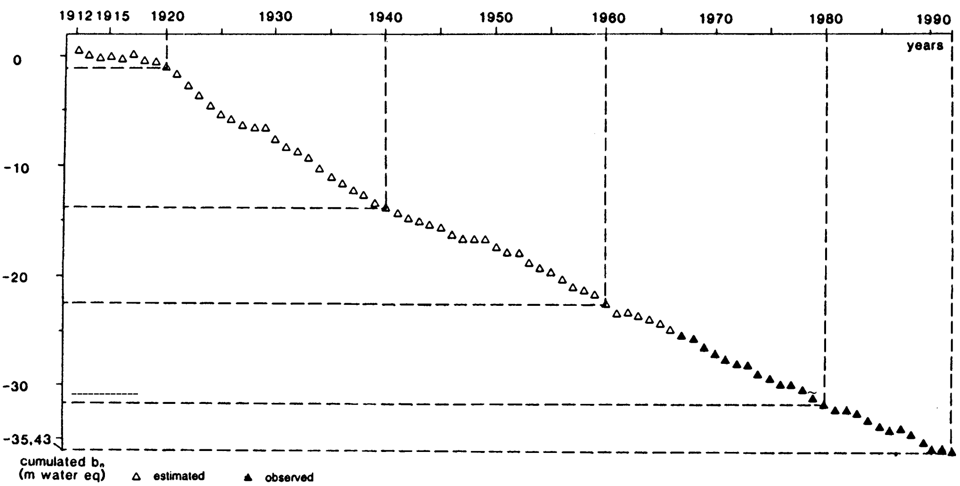

Fig. 3. Cumulative net balance of Brøggerbreen 1912-1992.

because of the climatic conditions with high melting and because the flow and the emergence velocity of the glacier is very small due to the cold glacier ice. In the lower part of the glacier, below 200 m a.s.l., the horizontal velocity is less than one metre per year, and thus the emergence velocity is only few centimetres per year. Based on air photos from 1977, a glacier map was constructed at the scale of 1:20,000 with a contour interval of 10 m. One of the ablation stakes was resurveyed in 1985. The vertical difference on the glacier surface was 5.20 m compared to the 1977 map. The cumulative net balance at this point over the same period was 4.95 in water equivalent, which is 5.45 m of ice. Direct measurements from the map and the surveying thus agreed well with the annual mass-balance measurements (Hagen and Liestøl 1987). This is typical for these small subpolar valley glaciers in Svalbard where the thin and outermost parts of the glacier are frozen to the ground.

Water Balance

The water balance equation for a partially glacierized catchment is composed of many components as discussed for instance by Young (1990). Potential runoff, Q_{pot}, is calculated from data derived from mass-balance measurements on the main glacier in the basin, Austre Brøggerbreen, covering 6.1 km^2 or almost 20% of the catchment area.

The following equation will be discussed

$$Q_{\mathrm{pot}} = Q_s + Q_p + Q_i + Q_g + Q_c - Q_e \tag{2}$$

where Q_{pot} is potential total runoff, or calculated runoff from water balance components, Q_s is snow melt runoff from ice-free areas, Q_p is runoff from rainfall, Q_i is the glacial component of discharge which includes ice melt, firn melt and snowmelt from the icecovered area, Q_g is groundwater discharge, Q_c is runoff from condensed water vapour and Q_e is evaporation.

The aim is to see if

$$Q_m \equiv Q_{\mathrm{pot}} \tag{3}$$

where Q_{pot} is potential total runoff, or calculated runoff from water balance compo-

The groundwater element, Q_g, is close to zero. The basin is in a permafrost area, but the taliks under the glacier are probably feeding the groundwater beneath the permafrost (Liestøl 1977). The groundwater term could then be negative in this case as meltwater is lost to the groundwater under the glacier. On the other hand a small, partly groundwater fed lake (Tvillingvatna) drains to Bayelva (Fig. 1) giving a small positive runoff.

The condensation of water vapour on the snow/ice surface during the summer must be taken into account. According to Sverdrup (1935) and Liestøl (1989) condensation may be responsible for 10-15% of the energy used for ablation on the glaciers in northwest Spitsbergen. The mean specific summer balance on Brøggerbreen

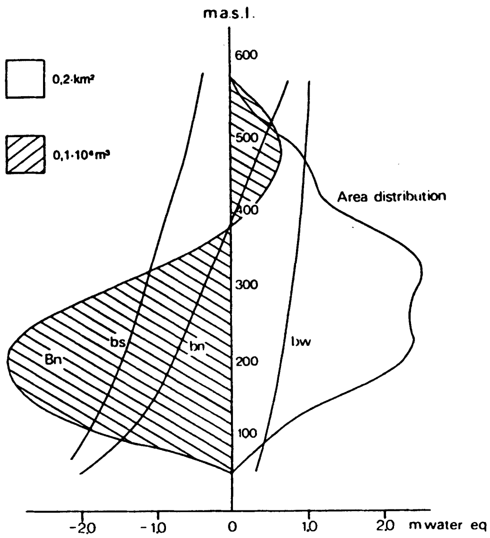

Fig. 4.
Mean values of specific winter, summer and net balance variations related to altitude on Brøggerbreen.

was 1.14 m from 1967 to 1991, or 19.5×10^6 m^3 in the total glacierized area (from Eq. (6)). Total mean melting caused by energy from condensed water vapour is then about 2.4×10^6 m^3. Since condensation of 1 g water vapour releases enough heat to melt 7.5 g ice condensed water vapour thus gives runoff, Q_c, of about 0.30×10^6 m^3 water.

Evaporation has not been studied carefully in the basin, but a mean value of 100 mm for glacier-free areas was used by Bruland (1991) based on the average of values used by several different authors. Evaporation also occurs on the glacier. In areas with exposed bedrock and little snow cover the evaporation is negligible. Using 100 mm in the rest of the field gives a maximum total evaporation, Q_e, of 1.5×10^6 m^3 including the glaciers. This figure is used as an average value each year in the water budget.

The three main components of the water balance are Q_s, Q_p and Q_i.

The runoff from melting of snow in ice-free areas, Q_s, is calculated from estimated snow distribution. The mean snow cover thickness for each hundred metre height interval, bw_i, is taken directly from the winter accumulation measurements on the glacier (Fig. 4). However, parts of the basin, especially in higher areas, are exposed to wind drift and thus little or no snow settles in these areas. Therefore we cannot use the area-altitude curve directly. Above 100 m a.s.l. a gradually greater part of the ice-free area is blown free from snow. A 15% decrease of snow covered area at 100 m intervals is used, so that at 0-100 m a.s.l. 100% cover is used, at 100-200 m a.s.l. 85% *etc*. For the years used in this calculation the mean snow magazine was ca. 5.6 $\times 10^6$ m^3 (see Table 1). The runoff from this snow melt is calculated as if all snow has melted

$$Q_s = \sum bw_i \, A_i \, (1.00 - 0.15\, i) \qquad (4)$$

where b_w is specific snow accumulation, $i \equiv 0$ (0-100 m a.s.l.), 1 (100-200 m a.s.l.) *etc.* and A_i is area of the snow-free part of the basin in the interval i.

The runoff from precipitation during the summer, Q_p, is calculated from estimated precipitation distribution. It is assumed that all precipitation in the summer comes as rain over the whole basin or if it comes as snow it all melts. The same altitude gradient as the winter precipitation on the glacier is used. That is, an annual gradient slightly less than 100 mm/100 m (db_w/d_z). That is equivalent to a 25% increase per 100 m altitude which is used in Eq. (5) based on the measured summer precipitation in Ny-Ålesund. The precipitation is calculated for each hundred metre interval using the whole field area

$$Q_p = \sum (p_0 (1 + 0.0025\, z_i) A_i) \tag{5}$$

where i is the elevation interval 1 (0-100 m a.s.l.), 2 (100-200) *etc.*, $z1 \equiv 50$, $z2 \equiv 150$ *etc.*, p_0 is the measured precipitation at the meteorological station in Ny-Ålesund multiplied by 1.1 for adjustment of approximately 90% catchment in the precipitation gauging station and A_i is the area of interval i.

The result was a relatively variable discharge caused by the summer precipitations, as can be seen in Table 1.

The runoff from melting of both snow and ice in the ice-covered areas, Q_i, is calculated on basis of the ablation measurements carried out on Austre Brøggerbreen (Fig. 4). The ablation or summer balance is measured at 12 stakes drilled into the glacier at different altitudes. The area-altitude distribution is almost the same in the whole basin as on Austre Brøggerbreen, therefore the ablation values are extended to the whole glacierized area of the basin. Thus the runoff is then given simply by

$$Q_i = bs\ 17.1\ \text{km}^2 \tag{6}$$

where b_s is specific summer balance on Brøggerbreen.

Table 1 – Water balance components for the years where runoff measurements exist. All values given in 10^6 m^3

Year	1974	1975	1976	1977	1978	1990	1991	mean
Q_s	5.45	5.65	5.22	5.51	5.43	5.43	6.67	5.60
Q_p	4.52	4.57	9.30	3.23	1.28	9.21	5.39	5.36
Q_i	28.55	18.63	20.00	14.90	22.40	24.11	13.51	20.30
Q_c	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Q_e	-1.50	-1.50	-1.50	-1.50	-1.50	-1.50	1.50	-1.50
Q_{pot}	37.32	27.62	33.32	22.44	27.91	37.55	24.37	30.06
Q_m	44.26	28.58	33.62	23.07	29.45	31.60 *	28.13	31.24

*) in 1990 a large and increasing leakage occurred under the crump weir in August/September.

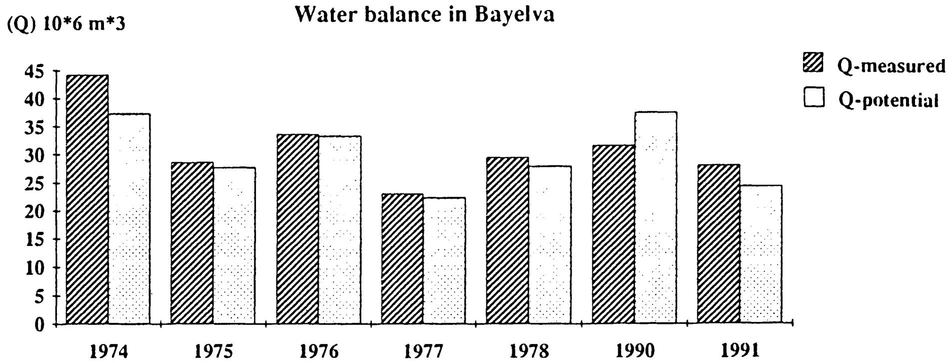

Fig. 5. Water balance in Bayelva basin during the seven years with runoff observations.

Discussion

The runoff from melting on the ice-covered areas, Q_i, is the major contributor to the total runoff. It is probably better to calculate runoff on the basis of the total summer balance on the glaciers and not divide it into two parameters, snow and ice melt. The net balance value will then be included in this value. The runoff could be corrected to an equilibrium year runoff by the glacier net balance value.

The mean net balance during the 25 years of observations was b_n = -0.42 m, corresponding to a runoff of $Q_n \equiv 0.42 \text{ m} \times 17.1 \times 10^6 \text{ m}^3 = 7.18 \times 10^6 \text{ m}^3$. That means that the runoff every year has been ca. 30% higher than in a year with equilibrium mass-balance on the glacier.

General models of runoff can give large errors, especially in small basins such as Bayelva. In small basins it is necessary to use local knowledge about the field conditions, the area/altitude distribution and the snow distribution. The runoff from precipitation during the summer, Q_p', may give some errors because a uniform altitude gradient of as much as 25% per hundred metre altitude increase may give too high values in the uppermost areas of the basin. As can be seen in Table 1, large variations occur in this term.

The observed period of only seven years is too short to give a reliable regression between measured total runoff, Q_m, and calculated potential runoff, Q_{pot}, but as demonstrated in Fig. 5. there is good agreement. If we exclude the unreliable year 1990 the correlation coefficient is as high as $r = 0.95$, and explains 91% of the variance (with $p \equiv 0.43\%$). The obtained linear regression of the six-year period gives the equation

$$Q_m = 1.24\, Q_{pot} - 4.42 \qquad (7)$$

which indicates that the calculated runoff based on mass-balance measurements gives a satisfactory estimate of the total runoff from the basin.

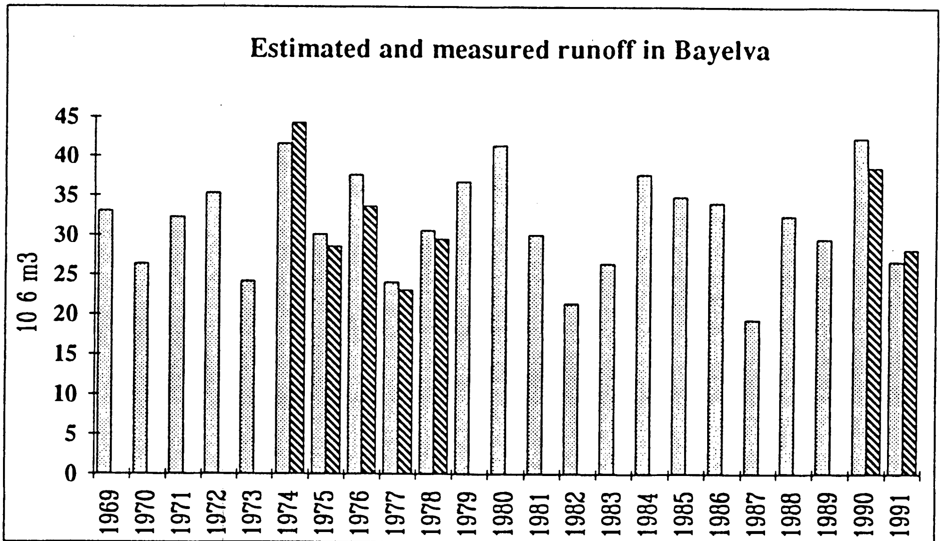

Fig. 6. Estimated (shaded) and measured (lined) annual runoff in Bayelva for the period 1969-1991.

The influence from the different components is mainly from the snow/firn/ice melt from the glaciers and from the summer precipitation (see Table 1). Thus, multiple correlation between the potential runoff, Q_{pot}, and the specific summer balance on Brøggerbreen, *bs*, and the summer precipitation (*p*6-8) at the meteorological station in Ny-Ålesund gives a very high multiple correlation coefficient of $r \equiv 0.99$, while $r(Q_{pot}/bs) \equiv 0.87$ and $r(Q_{pot}/p6\text{-}8) \equiv 0.57$.

The multiple regression analysis gives the equation

$$Q_{pot} \equiv 16.253\, b_s + 0.057\, p6\text{-}8 + 5.498 \qquad (8)$$

where *bs* is given in m, *p*6-8 is given in mm, and Q_{pot} in 10^6 m^3.

Using Eq. (8) and then Eq. (7) the total runoff from the basin can be calculated for the 25-year period of mass-balance observations 1967-1991 (Fig. 6).

In this water-balance discussion we have only compared potential (or simulated) runoff for the whole melt/runoff season and not the day-by-day variations. Runoff variations such as sudden emptying of glacier-dammed lakes does not influence the total result. The daily runoff will be affected by the glacier so that early in the melt season temporary storage and refreezing of meltwater will give lower runoff than expected from the melting. This water is, however, released later in the melt season. The runoff response to rainfall is in a similar way affected by the glacier.

The mass-balance measurements on the glacier enable us to estimate the total runoff from the basin fairly well, but not day-by-day variations simulated in models like the HBV-model which is commonly used in Norway. In the HBV-model the daily melting is calculated based on a degree-day factor and the number of degree days in each height interval. However, the total runoff can be simulated in years with no mass-balance measurements by simulating the summer balance. There is a strong correlation between the summer balance and the number of positive degree days (PDD) in Ny-Ålesund (see Eq. (1)). In this way the runoff series can be extended to periods where only meteorological data exists.

Conclusion

In Arctic areas, where a lot of catchment areas are partly glacierized, a considerable increase of the runoff can be expected from an expected temperature increase because both melting and precipitation will increase. This is not yet the case in Svalbard, however, as the summer balance has shown a stable or slightly decreasing trend. The winter balance has shown a slightly increasing trend. The net balance on Brøggerbreen has been negative since the mean summer temperature increased nearly 1°C from 1910 to 1920 (Lefauconnier and Hagen 1990). However, the net balance was slightly less negative in 1991 than 25 years ago. Over the long term the extra runoff from the glaciers will decrease in a stable climate like today because the glacierized areas will be reduced, especially at lower altitudes, and the size will adjust to the warmer climate. A period of increasing runoff will therefore be followed by a period of decreasing runoff. The length of the periods depends on the size and area/altitude distribution of the glaciers. This effect is described in the discussion of response time on the Hofsjökull Ice Cap in Iceland by Jóhannesson (1991).

In partly glacier-covered catchment areas, where mass-balance measurements are available, the potential total runoff from the basin can be well estimated just from the specific summer balance on the glacier together with summer precipitation data in the basin. In the basin Bayelva (31.5 km^2) where the glacier Austre Brøggerbreen covers about 20% of the area the correlation between the measured and estimated potential runoff was as high as 0.95 for a short period of only seven years. The three main runoff contributions were melting of snow in ice free areas, melting of snow and ice in glacierized areas and summer precipitation. The amount of winter snow precipitation has been fairly stable year by year, so the variations of the snow melt from ice free areas has been fairly stable too. Thus it is mainly the summer ablation on the glaciers and the summer precipitation that give the variations in the annual runoff from the catchment. The summer balance on the glaciers will include all extra runoff caused by the reduced mass of the glacier. In Bayelva this extra runoff resulted in about 30% higher total runoff from the basin than if the glacier was in equilibrium with zero net balance.

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