Water balance investigations in Svalbard

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This paper reviews and summarizes all known previous water balance studies in Svalbard. An updated water balance computation was then done for the three water catchments with the best data: Bayelva, De Geerdalen and Isdammen/Endalen for 10 hydrological years 1990–2001. The computations were based on the best available data and correction methods. Special emphasis was put on correction of precipitation data, both for catch errors and gradients in precipitation. Areal precipitation in the three catchments is more than two times the measured precipitation at the closest meteorological station: 548 mm/year in De Geerdalen, 486 mm/year in Endalen/Isdammen and 890 mm/year in Bayelva. Compared to this, average measured precipitation is only 199 mm/year at Svalbard Airport, close to Endalen/Isdammen and De Geerdalen, and 426 mm/year in Ny-Ålesund, close to Bayelva. Evaporation is not well understood in Svalbard; the best estimates indicate an average annual evaporation of ca. 80 mm/year from glacier-free areas, and no net evaporation from glaciers. Glacial mass balance has in general been negative in Svalbard during the last 40 years, leading to a significant contribution to the water balance, on the order of 450 mm/year on average. Annual runoff ranges from 545 mm in Endalen/Isdammen, 539 mm/year in De Geerdalen up to 1050 mm/year in Bayelva. Runoff computed from water balance compares well with observed runoff, and average error in water balance is less than ±30 mm/year in all three catchments.

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Hydrological data from Arctic regions are sparse, and Svalbard is no exception. There were, for example, no regular monitoring stations for river runoff before 1990 and even today there are fewer than five stations with continuous recording. Water resources can easily become a limiting factor for development of industry and tourism, and knowledge about hydrological processes constitute an important link between global change scenarios and consequences for the Arctic ecosystems. Both for scientific studies and water management, it is important to know the amount of water in storage in the catchments (as glaciers, snow, groundwater and lakes) and the flux of water into or out of the catchments as precipitation, evaporation and runoff.

Water balance or water budget calculations is a method used by hydrologists to assess the water resources within an area, and to verify that the different measurements of hydrological terms are consistent and gives results that are correct. The water balance concept is based on the fact that during some time (a day, a month, a year, etc.) the total input of water to an area, for example

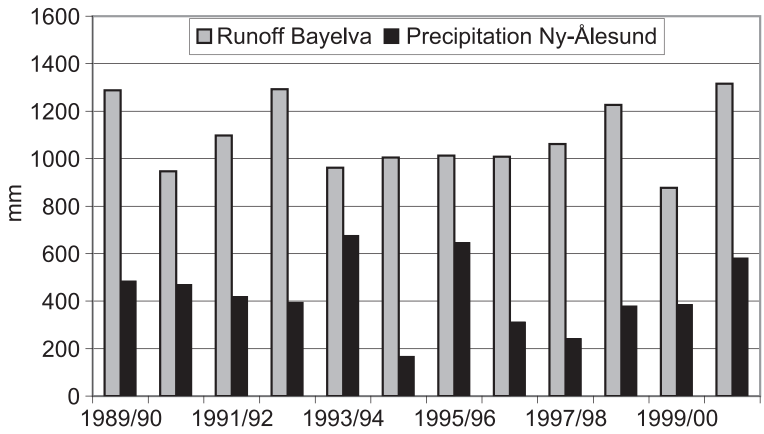

Fig. 1. Observed precipitation and runoff in Bayelva.

a river catchment, will be balanced by the total amount of water leaving the area and changes in storage within the area. No water can disappear since it has to be accounted for in the budget. The water balance can, in principle, be calculated for any area, large or small, but in practice the water balance is usually calculated for a river drainage basin, also called a catchment.

The usual formulation of the water balance equation for a river catchment is:

$$P_A - Q_S - Q_G - E_A \pm \Delta M = \varepsilon \,, \qquad (1)$$

where P_A is precipitation input (mm), Q_S is surface (river) runoff from the catchment (mm), Q_G is groundwater runoff from the catchment (mm), E_A is evaporation from the catchment (mm), ΔM is changes in water storage within the catchment (mm) and ε is an error term (mm). The error term ε should approach 0 if all the five terms on the left side of the equation have been determined correctly. The magnitude of the error term indicates the accuracy of the different terms of the water balance. The type of errors and their magnitude will be different in different hydrological regimes, depending on climatic, geological and topographical conditions, and the quality of measurements. In Arctic catchments many specific problems are encountered in the measurements.

Methodology—special problems in Arctic catchments

The problem of water balance computations in Arctic catchments is illustrated in Fig. 1. Here, the measured runoff in Bayelva (converted to mm) is compared to the measured precipitation at the nearest precipitation station at Ny-Ålesund (see Fig. 2). The comparison is done for 12 hydrological years (a hydrological year is from 1 October to 30 September) with simultaneous observations of runoff and precipitation. This is a striking example of what is sometimes called the "hydrological paradox". The paradox is that runoff seems to be much larger than precipitation. In reality, it should, of course, be the other way around, since all river runoff is ultimately generated from precipitation, and there will also be evaporation and possibly groundwater runoff removing some of the precipitation from the catchment. The paradox can be attributed to a combination of measurement errors, non-representative location of precipitation stations and net glacial melt during the period of study. By identifying and correcting these problems it is possible to establish the true value of each component in the water balance, and finally check the water balance in order to verify the computations. The computation of each individual term in the water balance, and some particular problems specific for Arctic climate are described below.

Precipitation

The term P_A in the water balance is the average or *areal precipitation* in the catchment. This term is based on observed (measured) precipitation, but it will usually be higher than measured precipitation since precipitation measurements are affected by a number of error sources. In addition, precipitation gauges may not be placed in representative locations in the catchment, compared

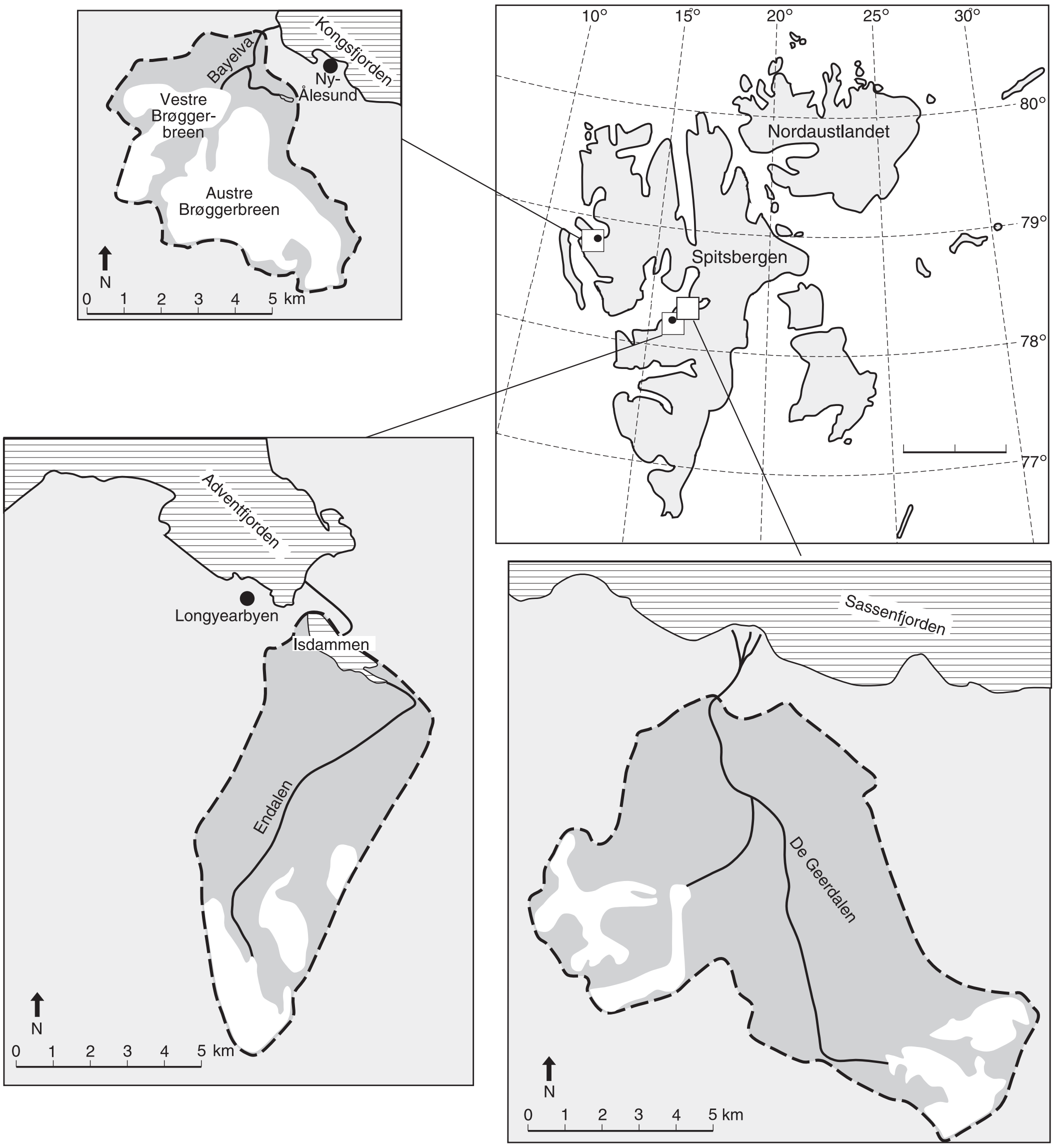

Fig. 2. Location of the three selected catchments in Spitsbergen, Svalbard: Bayelva, Endalen/Isdammen and De Geerdalen.

to the areal precipitation variation. One particular problem of great importance is that precipitation usually increases with elevation, while most precipitation gauges are located in the lowlands. This is a highly significant problem in Svalbard where all precipitation stations are located close to sea level, while catchments may reach up to more than 1000 m a.s.l.

The computation of areal precipitation in general is based on measurements in one or preferably several gauges located within or near the catchment. The computation usually consists of the following two steps. (1) The observed precipitation ($P_{O1}, P_{O2}, \dots P_{ON}$) is corrected for gauge catch errors to obtain true *point precipitation* values at the site of the precipitation gauges ($P_{T1}, P_{T2}, \dots P_{TN}$). (2) Areal precipitation (P_A) can then be computed as an areal average for the catchment. This is based on the corrected point precipitation data: $P_A = f(P_{T1}, P_{T2}, \dots P_{TN})$. The method

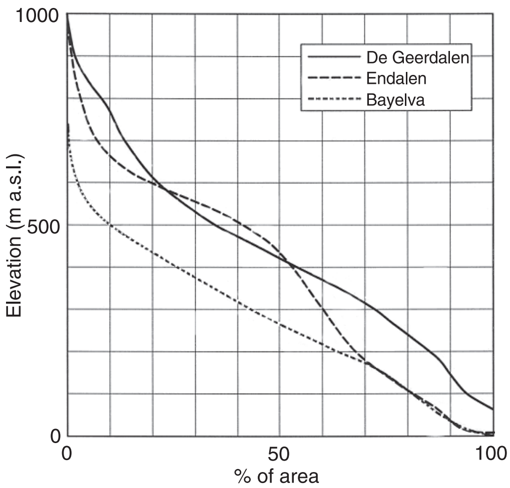

Fig. 3. Hypsographic curve for the three selected catchments.

for areal averaging must consider both regional and elevation gradients in precipitation distribution within the catchment.

It is well known that precipitation measurements—in particular the measurement of snow precipitation—are subject to large errors (see, e.g. Strutzer 1965, Bogdanova 1968, Larsson & Peck 1974 and Sevruk 1982). The measurement error nearly always leads to an observed precipitation that is less than the true point precipitation. Correction methods for gauges in the Nordic countries have recently been developed and reported by Førland et al. (1996). Error sources and correction methods were studied in the Climate Studies in the Arctic project, where one of the sub-projects was to investigate the difference between measured and true precipitation at Svalbard. Results from this study and other relevant studies are reported by Hanssen-Bauer et al. (1996). They conclude that "The seasonal ratio between true and measured precipitation varies between 1.26 for the summer and 1.70 for the winter. If it is supposed that the seasonal ratios which were found are typical for a normal year in Ny-Ålesund, the true normal (1961–1990) would be 550 mm, i.e. 50 % higher than the official uncorrected value" (p. 37).

Water balance calculations by Sand & Bruland (1999) used the correction factors found by Hanssen-Bauer et al. (1996): 1.26 in June–August, 1.45 in September–November, 1.70 in December–February, and 1.57 in March–May. These correction factors were applied for the precipitation gauges both in Ny-Ålesund and at Svalbard Airport.

Elevation gradients in precipitation

In mountainous catchments one usually finds that precipitation increases with increasing elevation, at least up to some elevation levels. In the Nordic countries it is quite common to observe precipitation gradients of 5 - 10 % increase per 100 m increase in elevation.

In Svalbard all precipitation stations are located near sea level, and therefore the measured precipitation here can be much lower than the average (areal) precipitation in the catchments which may extend up to elevations of 500 - 1000 m a.s.l. or more (Fig. 3). This problem was recognized when the first attempts on water balance calculations were planned from 1990 onwards. The first observational network for the study of precipitation gradients was set up in De Geerdalen and close to Longyearbyen. The average gradients found for precipitation during summer were 5 - 10 %/100 m. The true gradient may have been higher though, since the gauges located at higher elevations were more exposed to wind than those in lower and more sheltered areas (Killingtveit et al. 1994).

At Ny-Ålesund the orographic precipitation distribution was studied during the 1994 and 1995 summer seasons (Førland et al. 1997a). A gradient of 20 %/100 m was found for summer precipitation, at least for elevations up to 300 m. This led to the conclusion that "The orographic precipitation enhancement, and catch deficiency of conventional precipitation gauges may fully explain the apparent discrepancy between precipitation measured at Ny-Ålesund and runoff/mass balance estimates for the Bayelva catchment". This result corresponds well with Repp (1979), who found a gradient of 95 mm/100 m (ca. 20 %) and Hagen & Lefauconnier (1993, 1996) who used 25 %/100 m but who also pointed out that a linear gradient of 25 %/100 m might give too high values in the uppermost areas. Mercier (2001) reported average gradients of 100 mm/100 m in a small catchment near Zeppelinfjellet, which translates to ca. 12 %/100 m.

Sand & Bruland (1999) used a gradient of 25 %/100 m in the Bayelva catchment, with reference to Hagen & Lefauconnier (1993). In the Londonelva catchment they used a gradient of 31 %/100 m, a value found from analyses of snow survey data from the years 1996–98 in the same catchment.

Finally, they used a gradient of 14 %/100 m in the De Geerdalen catchment with reference to Killingtveit et al. (1994).

Precipitation gradients during winter cannot easily be studied by direct precipitation measurements due to the large problems of measuring snow precipitation in higher and more wind-exposed locations. Since snow in Svalbard usually accumulates without any significant melt events during the winter, it is possible to use snow on the ground as a measure for winter precipitation. This requires a careful selection of measurement sites to avoid problems due to wind redistribution of snow on the ground. Tveit & Killingtveit (1994) reported gradients of 85, 57, 20 and 85 mm /100 m for the four years 1991–94, based on analysis of snow surveys. This translates into relative gradients from 4 to 28 %/100 m, with an average around 14 %/100 m. Winther et al. (1998) studied regional distribution of snow in Svalbard as well as the elevation gradients. Their study was supplemented by Sand et al. (2003), who updated the results based on three years of snow surveys. The average gradient was 97 mm/100 m for the elevation range 100 - 1000 m a.s.l., which translates to 16 %/100 m.

Runoff

Runoff is usually the most reliably measured term in the water balance. Since runoff is an integrated response from the whole catchment, the problem of representativity of stations does not exist for this term. Still, there are other important problems and error sources, in particular in an Arctic catchment. Practically all continuous runoff measurements are done by calibrating a rating curve which shows the river flow (runoff) as a function of river water level (stage). The stage can fairly easily be recorded and the runoff computed as long as the rating curve is valid. Most errors in runoff records are related to problems in establishing calibration and the stability of the rating curve, while the stage measurements in itself is relatively simple to perform. Two of the most important problems sources in Arctic rivers are unstable bed profiles at gauging stations and ice and snow blocking the river profile.

In Svalbard, river runoff mostly occurs during a few months from June up to September. In the autumn all rivers freeze up completely, except short reaches of rivers fed by springs or in the front of some glaciers (Petterson 1994). During the freeze-up process, large amounts of bottom ice may be formed, blocking the river profile. Later, during the winter, snow is swept down into the river channel and thick snow drifts may form, especially in deep gorges and ravines. When the snowmelt starts in the spring or early summer, the runoff often increases quite rapidly, flowing into a river channel which is still blocked by ice and snow. In perennial rivers similar problems may occur when surface ice breaks up and creates ice-runs and ice-jams in the river. In all these cases, the water level in the river, which is the property measured at gauging stations, may increase much more than the flow. The problem will gradually disappear as snow and ice is eroded and melted, but its magnitude and duration may be very difficult to determine, especially at remote stations with automatic measurements.

Evaporation

Evaporation from a catchment occurs from water surfaces, soil surface and vegetation. The total evaporation from the catchment is called *areal* or *actual evaporation*. Areal evaporation is determined partly by the climate (potential evaporation) and partly by the wetness conditions in the catchment. In a dry desert, the potential evaporation may be very high, but the actual evaporation will be zero if there is no water. In Arctic catchments the potential evaporation during the summer may be very significant, due to high net radiation during days with 24 hours of sunshine. The amount of actual evaporation may still be small due to little vegetation, little rainfall and soils that easily dry up after snowmelt. Potential evaporation can be determined by measurements or by computations based on climatic data. Actual evaporation is usually computed as a fixed percentage of potential evaporation or as a function of potential evaporation and soil moisture conditions. It may also be computed as a residual term in a water balance computation.

Storage change

The most significant storage components generally considered in the water balance calculations are:

$$\Delta M = \Delta M_S + \Delta M_G + \Delta M_L + \Delta M_R , \qquad (2)$$

where ΔM_S is change in snow storage, ΔM_G is change in glacier storage, ΔM_L is change in lakes and river storage, ΔM_R is a residual term, including change in soil- and groundwater storage. Snow storage, lake and river storage and the residual term will normally show limited variations on a seasonal time scale. Glacier storage, however, normally show variations over a much longer time scales and the ΔM_G term may become very significant over a period of a few years. If the water balance calculation is done for a long time period (several years) most of these terms can usually be neglected, with the exception of ΔM_G. Also, if the water balance is done for hydrological years (e.g. 1/9–31/8 or 1/10–30/9) the storage terms (except ΔM_G) can usually be neglected. For shorter time steps (month, week, day) all the storage terms must be included in the calculation, which complicates the calculations considerably.

Previous work

Some of the elements in the water balance have been measured for a long time in Svalbard. Precipitation measurements have been made by the Norwegian Meteorological Institute from 1911 in Green Harbour, from 1916 in Longyearbyen and from 1950 in Ny-Ålesund (Førland et al. 1997b). Glacier mass balance measurements started 1966 at Brøggerbreen (J. O. Hagen, pers. comm 2002), while the first known systematic runoff measurements in Svalbard were started in Bayelva close to Ny-Ålesund from 1974 (Repp 1988a, b). Regular and continuous runoff measurements have been operated by the Norwegian Water Resources and Energy Directorate since 1989 in Bayelva. Later, regular runoff measurements have been established in three other catchments: Endalen/Isdammen and De Geerdalen close to Longyearbyen, and in Londonelva near Ny-Ålesund. Evaporation measurements are almost non-existent, but a few measurements were done by the Foundation for Technical and Industrial Research at the Norwegian Institute of Technology (SINTEF) in Ny-Ålesund in 1992 and 1993 as part of the Land Arctic Physical Processes (LAPP) project (Institute of Hydrology et al. 1999).

The first known water balance Study in Svalbard was done near Kings Bay in 1968 (Geoffray 1968). Data from Repp's studies in Bayelva were used by Bruland (1991) in an attempt to establish the water balance and calibrate hydrological models in Svalbard. These data were also used by Hagen & Lefauconnier (1993). Some other river flow measurements have been reported by Russian scientists (Gokhman & Khodakov 1986) and Polish scientists (Pulina et al. 1984). None of these studies included a complete water balance computation.

Jania & Pulina (1994) reported on the results from several Polish research projects in Svalbard, and summarized the results in tables for water balance and chemical denudation in the Werenskioldbreen basin for one hydrological year (1979/80) and for several unidentified basins in the Hornsund area. The main results are summarized in Table 1.

Water balance computation for catchments in Svalbard based on Norwegian studies was presented at the Northern Research Basins meeting in Ny-Ålesund in 1994 (Killingtveit et al. 1994). This study was based on the observations initiated by the Norwegian National Committee for Hydrology from 1991 to 1993 in the three catchments—Bayelva, De Geerdalen and Endalen/Isdammen. In this paper the results from a literature search were also reported, but no other studies beyond those already noted could be found.

Several studies have been done concerning winter water balance and possible groundwater flow to Tvillingvatnet, near Ny-Ålesund, and Isdammen, near Longyearbyen. These are summarized in the section on groundwater runoff.

Sand & Bruland (1999) presented the water balance for the Bayelva, Londonelva and De Geerel-

Table 1. Water balance results from Polish research projects in Svalbard reported by Jania & Pulina (1994).

	Glaciated catchments	Permafrost basins
P_A	1070 - 1340 mm/year	800 mm/year
Q_S	1680 - 1920 mm/year	710 mm/year
E_A	90 mm/year	90 mm/year
ΔM_G	670 - 700 mm/year	0 mm/year

Table 2. Water balance results from catchments in Spitsbergen reported by Sand & Bruland (1999).

	Bayelva	Londonelva	De Geerdalen
P_A (mm/year)	968	595	478
E_A (mm/year)	46	100	108
ΔM_G (mm/year)	–456	0	–21
Q_S (mm/year)	1053	411	525
ε (mm/year)	–7	118	–134

va catchments for the years 1991 to 1998 (see Table 2).

For years when snow survey data existed they determined the areal winter precipitation based on the snow survey data rather than measurement of precipitation. For other years, the areal precipitation was estimated from precipitation measurements only.

A recent work (Mercier 2001) includes a summary from a large number of studies of geomorphology, glaciology and hydrology in Svalbard, including studies of the components in the hydrological balance (water balance) for Austre Lovénbreen in Kongsfjorden and for a 0.1 km^2 non-glaciated area near Zeppelinerfjellet near Ny-Ålesund. Some of the results from this report are included in subsequent sections.

Catchments selected for water balance study

In this paper, data from the three catchments with the best data coverage—Bayelva, De Geerdalen and Endalen—will be used. A brief description of the different observation data (runoff, precipitation, evaporation and glacier balance) is given in the following sections. The location of the catchments and a simplified map of each catchment is shown in Fig. 2. The area–elevation distribution within each catchment (hypsographic curve) is shown in Fig. 3. A summary of the most important data for each catchment is given in Table 3.

Runoff measurements–stations and records

Surface runoff—Bayelva. Runoff measurements in Bayelva started in 1974 (Repp 1979). These measurements ended in 1978, but were resumed in 1990 as part of an initiative taken by the Norwegian National Hydrological Committee in 1987. Measurements during the first year are considered unreliable due to an unstable river bed. In 1988 the river profile was stabilized by a concrete Crump-type weir and a permanent and stable rating curve could be established (Skretteberg 1992). The main operational problem now is caused by snow blocking the weir at the start of the snowmelt season, leading to errors in calculation of river discharge. This is corrected for as far as possible, but the resulting accuracy is not precisely known.

Table 3. Data for the three catchments Bayelva, De Geerdalen and Isdammen/Endalen. The minimum elevation is where the runoff gauging station is located

	Area (km^2)	Elevation (m a.s.l.) Min.	Average	Max.	% glaciers
Bayelva	30.9	4	265	742	55
De Geerdalen	79.1	40	410	987	10
Isdammen	34.4	3	427	1015	17
Endalselva	28.8	4	427	1015	20

Surface runoff—De Geerdalen. In the autumn of 1990 a second runoff station was established in De Geerdalen. The station is located in a narrow gorge with stable bedrock profile close to the outlet of the river, at Hyperittfossen (Fig. 2). The station has been in routine operation since summer 1991. The main operational problems here are related to ice and snow blocking in the narrow gorge.

Surface runoff—Isdammen/Endalen. The first station was established early in the summer of 1992, in the outlet from Isdammen, the water supply reservoir for Longyearbyen (Fig. 2). Here, the main operational problems were caused by uncertain rating curves and ungauged leakage in the outlet structure. Later, the station was re-established in Endalselva, upstream of a road culvert close to the inlet to Isdammen. At this site bottom ice build-up in the river profile seems to be the main operational problem, possibly also some leakage outside the main culvert. There is some uncertainty in the drainage area for these catchments, since the glacier Bogerbreen may also have some drainage to another catchment.

Annual runoff for hydrological years for the three catchments is shown in Table 4. Average monthly runoff (mm/month) is shown in Table 5 and the seasonal distribution of the runoff over the year is shown in Fig. 4. It is evident from Fig. 4 that runoff occurs mainly in June–September, with maximum runoff occurring in July. The runoff is dominated by snowmelt in June and July, while in August and September the runoff mainly comes from rainfall and glacial melt. The high percentage of glaciers in the Bayelva catchment gives a relatively higher runoff in August and September than in the two other catchments.

Groundwater runoff. Due to the permafrost there is usually no flow in groundwater below the

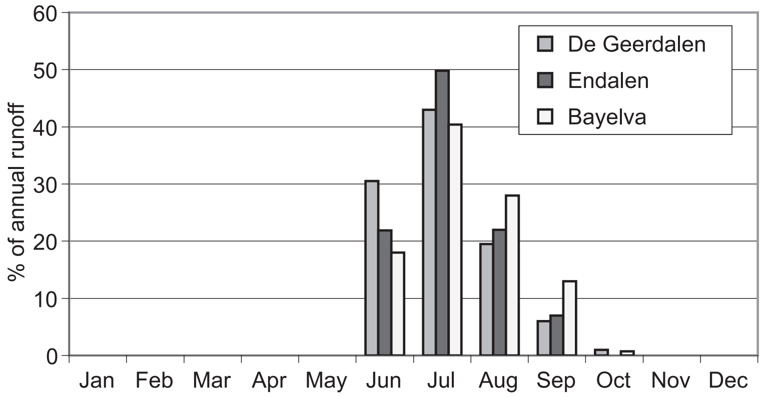

Fig. 4. Seasonal variations in runoff for the three selected catchments. Monthly averages computed for the observation period.

active zone (1 - 2 m) and therefore probably no groundwater flow directly to the sea. Exceptions may be groundwater flow from recharge areas under temperate glaciers and discharge through taliks under lakes or directly to the sea.

Speculations concerning possible groundwater inflow to the water supply reservoirs for Ny-Ålesund and Longyearbyen (Winther 1994) spurred special studies of the winter water balance for these reservoirs and their catchments. For Tvillingvatnet (Ny-Ålesund) there was previously documented winter inflow from groundwater in the 1920s. This groundwater flow was probably generated by recharge below the temperate basal part of the glacier Austre Brøggerbreen (Haldorsen & Heim 1999). Recent studies during 1990s (Sandsbråten 1995) did not confirm these results, but flow may have been reduced due to reduced infiltration area as the glacier has retreated significantly (Haldorsen & Heim 1999). Groundwater recharge in the Isdammen reservoir near Longyearbyen have been postulated as a possibility. Studies during the winter 1999/00 have not lead to conclusive evidence of any groundwater inflow (Klungland 2000).

There are no data to confirm or exclude the possibility of groundwater flow directly to the sea in Svalbard. Halvorsen & Heim (1999) did a detailed investigation along Kongsfjorden in the Ny-Ålesund area but could not find any indications of springs discharging along the coast or into the fjord. Therefore, in the water balance calculation presented here, it is assumed that no significant groundwater flow exists into or from the three catchments studied.

Table 4. Annual runoff (mm/year) for the three catchments.

Hydrol. year	Bayelva	De Geerdalen	Endalen
1990	1288	573	
1991	947	489	
1992	1097	641	486
1993	1292	429	596
1994	962	481	
1995	1005	463	429
1996	1012	596	555
1997	1008	605	608
1998	1061	472	611
1999	1227	593	534
2000	877	586	
2001	1316	573	
Average	1091	539	545

Table 5. Seasonal variation in runoff, mm/month, average for years 1990–2001.

Runoff (mm)	Bayelva	De Geerdalen	Endalen
January	0	0	0
February	0	0	0
March	0	0	0
April	0	0	0
May	0	1	0
June	201	164	109
July	437	233	247
August	317	106	114
September	111	33	34
October	4	4	0
November	0	0	0
December	0	0	0

Precipitation measurements

Stations and data records

Bayelva. There are no regular precipitation measurements in the Bayelva catchment, but the meteorological station in Ny-Ålesund is located quite close to the catchment. Here, regular precipitation measurements have been made since 1950. In addition, various studies concerning precipitation correction and precipitation distribution have been done. One of the most interesting is a study of precipitation distribution and precipitation gradients carried out by the Norwegian Meteorological Institute (Førland et al. 1997a). In other studies precipitation has also been estimated indirectly through snow measurements and glacier mass balance measurements within the catchment. These measurements are later used to establish precipitation–elevation gradients.

De Geerdalen. There are no regular precipitation measurements in the catchment and the closest meteorological station is located at Svalbard Airport, about 20 km south-west of the valley De Geerdalen. A number of precipitation stations were operated for a few years in the early 1990s as part of the first water balance studies initiated by the Norwegian Hydrological Committee (Killingtveit et al. 1994). A network of snow measurement stations has also been operated since 1991, making it possible to estimate winter precipitation indirectly (Tveit & Killingtveit 1994). These measurements have been used to estimate precipitation–elevation gradients in the catchments (Killingtveit et al. 1994).

Isdammen/Endalen. There are no regular precipitation measurements in the catchment and the closest meteorological station is located at Svalbard Airport, about 10 km west of Isdammen. A number of precipitation stations were operated a few years in the early 1990s as part of the first water balance studies. These measurements have been used to estimate precipitation–elevation gradients in the catchments (Killingtveit et al. 1994).

Annual measured precipitation in Ny-Ålesund and Svalbard Airport is shown for the hydrological years 1990/91 to 2000/01 in Table 6. Average (normal) monthly precipitation for the two stations is shown in Table 7.

Areal precipitation

Precipitation correction factors based on previous studies from Svalbard (Repp 1979; Hagen & Lefauconnier 1993, 1996; Tveit & Killingtveit 1994; Hanssen-Bauer et al. 1996; Sand et al. 2003) and other relevant studies in other Arctic catchments were used in this water balance calculation, leading to an average correction of 1.15 for rainfall and 1.65 for snow precipitation for Ny-Ålesund data and slightly higher values (1.15 and 1.75) for Svalbard Airport data. In these water balance computations a gradient of 15%/100 m was selected for the Isdammen/Endalen and Bayelva catchments, and 20%/100 m for De

Table 6. Annual precipitation data for stations at Ny-Ålesund and Svalbard Airport (mm/year).

Calender year	Ny-Ålesund	Svalbard Airport
1990	479	157
1991	502	257
1992	381	194
1993	674	262
1994	385	220
1995	256	159
1996	547	234
1997	390	217
1998	248	92
1999	348	187
2000	519	203
2001	487	185
Average	431	196

Table 7. Precipitations averages (mm/month) for the period 1961–1990 based on data from stations at Ny-Ålesund and Svalbard Airport.

	Ny-Ålesund	Svalbard Airport
January	32	15
February	36	19
March	45	23
April	23	11
May	18	6
June	18	10
July	28	18
August	38	23
September	46	20
October	37	14
November	33	15
December	31	16
Sum	385	190

Geerdalen.

Observed precipitation was first corrected for catch errors and then for elevation gradients, giving the average (areal) precipitation for each of the catchments. For catch errors the rain correction factor was applied for months with air temperature > 0 °C and snow correction factor for months with air temperature < 0 °C. The results of these computations are given as annual values in Table 8 for the Bayelva catchment. The same computations were done for the two other catchments. This is the final and total precipitation input to the three catchments and it is used in the subsequent water balance computation.

Evaporation measurements

Evaporation measurements have been and remain very scarce in Svalbard. A survey by Bruland (1991) found only one reference to previous measurements in Svalbard. Based on this observation and a few data from other Arctic sites, Bruland estimated an actual average annual evaporation of 100 mm/year. This value was later also used by Hagen & Lefauconnier (1993, 1996). In the final report from the LAPP project (Institute of Hydrology et al. 1999) the use of evaporation data in water balance computations is discussed with reference to Hagen & Lefauconnier (1993) and Killingtveit et al. (1994). The value of 100 mm/year is used, the report stating that "Still, no better estimate exists, and we have used the same value in our study" (p. 38). Net evaporation from glaciers was assumed to be 0.

Table 8. Areal precipitation calculation in Bayelva (mm/year).

Hydrological year	Observed precip.	Catch correction	Elevation correction	Areal precip.
1990/91	472	252	293	1016
1991/92	420	182	243	845
1992/93	396	213	247	856
1993/94	678	369	424	1472
1994/95	169	84	102	355
1995/96	648	348	403	1398
1996/97	312	157	190	659
1997/98	242	148	158	548
1998/99	380	175	225	780
1999/00	387	148	217	751
2000/01	582	207	320	1109
Average	426	207	256	890

Jania & Pulina (1994) used 90 mm/year in their water balance calculations. This value seems to be based on calculations from meteorological data "due to difficulties in taking measurements (a large error range is likely)" (p. 62).

To improve evaporation estimates, a Class A Evaporation pan was installed in Ny-Ålesund in 1992 and operated by SINTEF. Some early results from the measurements are reported in Killingtveit et al. (1994). The annual pan evaporation was estimated to 166 mm, based on pan measurements and some computed values where a regression equation between evaporation and air temperature was used to infill data gaps. The average actual evaporation from non-glaciated catchments was estimated to 120 mm/year in the Ny-Ålesund area, at an elevation of 10 m a.s.l.

Mercier (2001) reports computed potential evaporation for the years 1969–1995, based on both the Turc and the Penman formulas. Average computed values were 200 mm/year (Penman) and 51 mm/year (Turc). The large deviation between the two methods is discussed and it seems that most confidence is placed on the results from the Turc formula.

In this study a computation of potential evaporation as a function of air temperature was used. This function was calibrated by regression analysis using SINTEF's evaporation observations in Ny-Ålesund and air temperature data from Ny-Ålesund. The computed average annual potential evaporation for the 12-year period 1989–1991 was 138 mm/year for an area close to sea level in Ny Ålesund, computed from air temperature data and assuming a Pan coefficient of 1. Evaporation from snow or glaciers is not included. This value can be compared to data from Axel Heiberg Island (80° N) where Ohmura (1982) found an average evaporation of 138 mm/year. This value also included an estimated value of 20 mm/year of sublimation from snow.

Using the regression model and observed air temperature data the average evaporation from glacier-free areas could be computed for each year, using an average lapse rate of –0.6 °C/100 m. The results were 80 mm/year in Bayelva and 82 mm/year in De Geerdalen and Endalen—about 50 mm/year less than potential evaporation close to sea level.

Net annual evaporation from glaciers is assumed to be 0, as in previous studies in Svalbard (Hagen & Lefauconnier 1993, 1996; Institute of Hydrology et al. 1999). This assumption can be questioned, but it has not been possible to find better estimates from studies in Svalbard. There will probably be some losses by sublimation from dry snow and blowing snow but also some input by sublimation on ice during summer months. The net balance between losses and gains by sublimation on glaciers in Svalbard is probably small but cannot be verified yet. More studies need to be done. If such errors exist, positive or negative, it will add up in the error term in the water balance.

Using these data and the percent of glaciated area for each catchment (Table 3), the following values for average annual actual evaporation were computed for the catchments:

Bayelva, catchment average 80 mm/year * 0.45 = 38 mm/year at 265 m a.s.l.

De Geerdalen, catchment average 82 mm/year * 0.90 = 72 mm/year at 410 m a.s.l.

Endalen, catchment average 82 mm/year * 0.80 = 66 mm/year at 427 m a.s.l.

Storage terms

If the water balance is computed on an annual basis and for hydrological years, most of the storage terms in Eq. (2) can be neglected. Using a hydrological year from 1/10 to 30/9, we can assume that changes in snow storage, lakes, groundwater and soil moisture from one year to another can be neglected.

Lake storage is only important in Endalen/Isdammen but here the lake level has been measured and the lake is always filled to the same (maximum) level at the beginning of the winter season. Due to the deep permafrost there is no groundwater recharge from the surface except possibly below some of the glaciers. Such groundwater recharge has been not been identified in these three catchments, though there may be some small recharge under Vestre Lovénbreen. (Haldorsen & Heim 1999). If any recharge exists it is probably very small; there are no indications of substantial changes from year to year. There are, to our knowledge, no indications that water content in the active layer changes significantly from year to year. However, no measurements are available to prove this assumption. Theoretically, a very dry summer and autumn could dry out the soil moisture in the active layer, leaving a deficit that would fill up next spring. Also, there are no wetlands or icings that could store and "carry over" water from one year to another. Seasonal snow cover is always melted before the end of September and new snow cover usually starts to build up from October. Therefore, it seems acceptable to assume that all these storage terms can be neglected, except possibly some changes in soil moisture in the active layer. Since we have no data to compute such changes, the possible errors will contribute to the error term in the water balance. The change in glacier mass balance from year to year is very important and must to be included in the water balance.

Mean annual net mass balances for a number of Spitsbergen glaciers have been studied for many years, some back to 1951. At Austre Brøggerbreen, the annual mass balance has been studied since 1967, at Longyearbreen from 1977 to 1982

Table 9. Glacier mass balance for Austre Brøggerbreen (in m) for hydrological years 1974/75 to 2000/01.

Hydrological year	Winter	Summer	Total
1974/75	0.78	–1.09	–0.31
1975/76	0.72	–1.17	–0.45
1976/77	0.76	–0.87	–0.11
1977/78	0.75	–1.31	–0.56
1978/79	0.77	–1.48	–0.71
1979/80	0.75	–1.27	–0.52
1980/81	0.46	–1.01	–0.55
1981/82	0.64	–0.68	–0.04
1982/83	0.70	–0.97	–0.27
1983/84	0.69	–1.42	–0.73
1984/85	0.93	–1.48	–0.55
1985/86	0.98	–1.3	–0.32
1986/87	0.82	0.6	0.22
1987/88	0.61	–1.13	–0.52
1988/89	0.56	–1.01	–0.45
1989/90	0.75	–1.41	–0.66
1990/91	0.92	0.79	0.13
1991/92	0.69	–0.89	–0.1
1992/93	0.54	–1.57	–1.03
1993/94	0.79	–0.95	–0.16
1994/95	0.56	–1.34	–0.78
1995/96	0.78	–0.95	–0.17
1996/97	0.50	–1.12	–0.88
1997/98	0.65	–1.78	–1.13
1998/99	0.51	–0.87	–0.36
1999/00	0.41	–0.51	–0.11
2000/01	–	–	–0.45

and at Bogerbreen from 1975 to 1986 (J. Kohler, pers. comm. 2002). Annual results are given in Table 9. The average annual mean net balance during the observational period is given below:

Brøggerbreen 1967–2002, –450 mm/year

Bogerbreen 1975–1986, –430 mm/year

Longyearbreen 1977–1982, –550 mm/year

For water balance computations in Bayelva we used the changes measured at Brøggerbreen directly. For the water balance computations in the De Geerdalen and in Endalen/Isdammen there exist no glacier mass balance data for the glaciers in the catchments for the period when runoff has been measured. Since the Bogerbreen and Longyearbreen glaciers are much closer to these catchments than Brøggerbreen, we assumed that the Bogerbreen and Longyearbreen glaciers provide better information on glacial mass balance than Brøggerbreen. In lieu of direct glacier mass balance data in De Geerdalen and Endalen/Isdammen, we used annual changes measured at Brøggerbreen as an index of glacier mass balance, scaled by the difference between the glaciers Bogerbreen and Longyearbreen and Brøggerbreen during the overlapping measurement periods. The computed scaling factor is 1.06, i.e. changes in glacier storage in De Geerdalen and Endalen are computed as 1.06 times changes at Brøggerbreen, per unit area.

Table 10. Water balance for the De Geerdalen catchment in hydrological years 1990/91 to 2000/01: $P_{winter}+P_{summer}+\Delta_{glaciers}-Q-E=\varepsilon$. All terms are in mm.

Hydrological year	P_{win}	P_{sum}	$\Delta_{glaciers}$	Q	E	ε
1990/91	504	176	-14	573	70	23
1991/92	329	270	11	489	69	52
1992/93	503	134	109	641	93	12
1993/94	455	254	17	429	45	252
1994/95	224	115	83	481	77	–136
1995/96	561	189	18	463	53	252
1996/97	347	197	93	596	50	–8
1997/98	254	68	120	605	103	–266
1998/99	218	232	38	472	69	–54
1999/00	316	208	12	593	65	–122
2000/01	288	180	48	586	95	–166
Average	364	184	49	539	72	–15
Std. dev.	122	60	45	72	19	162

Water balance calculation

The water balance for Bayelva was calculated annually from data given in Tables 4, 8 and 9. The results are summarized in Table 10.

The water balance for De Geerdalen and Endalen/Isdammen was calculated similarly and the results are summarized as average for the whole computational period in Table 11, together with the results from Bayelva.

Discussion of results

The average water balance is good for all three catchments, with an average error term (imbalance) close to 0. There are, however, large deviations in some years which cannot easily be explained. A correlation analysis shows that there is still a strong correlation between the annual error term and winter precipitation. This indicates that the residual errors are probably related to problems of precipitation correction and areal precipitation computations. The results show very clearly the large difference between observed precipitation and areal precipitation computed within the catchments. The observed precipitation has to be multiplied by a factor on the order of 2 to compensate for errors in measurements and non-representative locations. The glacial mass balance term also makes a large contribution to the water balance and possible errors here will easily contribute significantly to the errors in some years. The evaporation is usually the most uncertain term in water balance computations. The results here cannot verify or disprove the evaporation estimates since the error terms in many years is on the same order of magnitude as the evaporation.

Comparing our results with the results reported by Jania & Pulina (1994), both the measured runoff and precipitation estimates are considera-

Table 11. Water balance for all catchments – Annual average for hydrological year ($P_{winter}+P_{summer}+\Delta_{Glaciers}-Q-E=\varepsilon$. All terms are in mm.

Catchment	P_{win}	P_{sum}	$\Delta_{Glaciers}$	Q	E	ε	Std ε
Bayelva	597	277	245	1050	37	31	230
De Geerdalen	364	184	49	539	72	-15	162
Endalen/ Isdammen	321	158	101	545	66	-14	106

bly lower in this study. It should be kept in mind the catchments investigated by Jania & Pulina (1994) are all located in the Hornsund area, in southern Spitsbergen, while our catchments are located in the central and north-western parts of the island. Sand et al. (2003) did a study of regional snow distribution on Spitsbergen which indicates that the Hornsund area receives approximately twice as much precipitation during the snow accumulation period (October–May) as the central region.

So far, the results from the water balance studies carried out in Svalbard have not been evaluated against water balance studies from other regions of the Arctic. However, the results from Svalbard will be part of a recently initiated study which will be an intercomparison of water balance in Arctic experimental watersheds (D. L. Kane, pers. comm 2003).

Further studies—recommendations

The results show that the calculated water balance in Svalbard still cannot be considered good enough to assess the individual components of the hydrological cycle with fair accuracy. Even though the average balance (error term) in the three catchments is close to zero, errors in individual years are still considerable. This indicates that it is still necessary to improve data collection and possibly also correction methods, in particular for precipitation and glacial net balance.

We recommend more detailed investigations concerning precipitation distribution, in particular the distribution during winter, when most of the precipitation falls. Snow measurements can be used to study amount and distribution of seasonal snow. Such data can be useful both to improve methods for precipitation correction and methods for computing areal precipitation in Svalbard.

Even if evaporation is not a dominant factor in the water balance, it would be very useful to improve the data base and we recommend that regular measurements should be established to acquire more precise data and to study seasonal and interannual variations in evaporation. Also, it would be useful to study and collect data on the evaporation from snow since this has not yet been studied in Svalbard.

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