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Characteristics of the polar hydrological year 1979/1980 in the basin of the Werenskiold Glacier, SW Spitsbergen

ABSTRACT: This paper contains thsults of hydrological and hydrochemical investigations carried out in the basin of Werenskiold Glacier against the background of determining climate elements. It also gives chosen elements of the water balance and mass balance determined from year-long investigations of the polar hydrological year 1979–1980.

Key words: Arctic, Spitsbergen, hydrology, water balance, chemical denudation

1. Introduction

In the southwestern part of the Wedel-Jarlsberg Land in West Spitsbergen there is the small Werenskiold Glacier, which has been the object of detailed investigations of Polish polar expeditions, beginning with the III International Geophysical Year, i.e. since 1957. These investigations were continued every year until 1961 and resumed after a 9-year break in 1970–1975 and subsequently from 1978 to 1982.

Based from the glaciological station[1]) built by Wrocław University, an ambitious reaearch programme was begun. Investigations were performed only in the summer season, except for the years 1957/1958 and 1979/1980. The results of the recent year-long research cycle are the subject of the present paper.

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[1]) This station was named after Stanisław Baranowski, an outstanding polar researcher, the head of expeditions of Wrocław University, who died in 1978 in an accident on King George.

2. A geomorphological draft characterization and remarks on the geological structure of the basin of the Werenskiold Glacier

The Werenskiold Glacier lies in deep valley which cuts across the coastal mountain range northeast of the outlet of the Hornsund Fiord. The topographical basin of this glacier, enclosed by the bank of terminal moraines, covers 44 km². According to the state of 1979/1980, the Werenskiold Glacier covers 64 per cent of the basin area (28 km²). The remaining part consists of the unglaciated forefield of the glacier (6 km²) and unglaciated mountain slopes and ridges (10 km²). In 1979 the front of the Werenskiold Glacier was withdrawn by 1.5 to 2.5 km with respect to its maximum range of 1936 and the length of the glacier decreased from 8.5 to 7 km. Similarly, the thickness of the ice decreased by a dozen-odd per cent. At present the mean thickness of the glacier is about 100 m. The maximum thickness of the glacier occurs in the central cirques. It is 250 m (Mocheret, Zhuravlov 1980; Czajkowski 1981). The altitude of the rock bottom of the valley is 30–70 m a.s.l. in the lower part, about 100 m a.s.l. in the central part and 150–250 m above sea level in the upper part, whereas the bottom of the central glacial cirque is at 100 m over the sea level. The morphology of the bottom of the valley indicates the presence of three glaciers, each related to its own glacial cirque. The northern glacier, called the Kvisla Glacier, is fed by the Skilryggbreen. The central glacier has the greatest glacial cirque, at the outlet of the Slyngfjellbreen. The smallest, southern glacier is fed by the Angellissen and possibly by the southern cirque of the firn field. These glaciers are separated from one another by median moraines, the most distinct of which is the one between the Kvisla and the central glaciers.

Each of the glaciers is drained by its own stream flowing from partly open glacial channels at the front of the glacier. Within the internal outwash these streams join into the Glacial River of the Werenskiold Glacier, which cuts across the terminal moraine and flows into the Nottingham Bay. Water from the basin of the Werenskiold basin began to be drained by one river only in 1969/1970. Previously the Kvisla Glacier, and also possibly in part the central glacier, had been drained by the Kvisla River which cut across the belt of terminal moraines under the slope of the Jens Erikfjellet (part of the water flowed out through channels in the dead ice) and flowed into the Nottingham Bay.

The surface of the Werenskiold Glacier and the distribution of cracks are to a large degree affected by the morphology of the rock bottom of the valley. Therefore, on the surface of the glacier there are ample troughs over rock depressions. In the ablation zone these troughs form closed oval basins drained by a system of underground channels. The greates of such basins was located in the central part of the glacier (the outlet of the Skilrygg Glacier); it is drained by several wells which it was possible to explore down to a depth of bellow 40 m[2]). One of them led to a large cave which was a part of a horizontal system of galleries situated at a depth of below 50 m beneath the surface of the glacier. This system collected water from wells in the vicinity and may have been fed by the stream from the Slyngfjell Glacier. The other synclines, with smaller size, are situate at the outlet of the Angell Glacier and in the central part of the tongue of the Werenskiold Glacier. One of them takes water to a well which connects to a horizontal cave reaching as deep as 39 m. This cave is located at a point deep cracks caused by the passage of the glacier over rock module occur. Some smaller hollows are drained superficially in the direction of the glacier front (e.g. Zimna Woda) or to marginal streams. These basins on the surface of the Werenskiold Glacier function for a short time which is determined by the zone of snow and ice thawing moving up the glacier. The largest basin begins to function at the end of the hydrological year. Wells freeze in middle autumn, while water gathering on the surface forms naled ice cover.

In the coastal zone of the Werenskiold Glacier there has developed a typical drainage system which takes water from the unglaciated slopes of the valley and the surface of the glacier. At places where the lateral glacier has prevented surface or subsurface outflow at a small depth, a marginal hollow, resembling a carst swallow hole, has arisen. The classical from of this type occurs underneath the Eimfjellet.

The Werenskiold Glacier, like the other glaciers in Spitsbergen, formed during the most recent short glacial epoch, following the climate optimum at the time of the Viking expansion. Over this optimum period, from 750 to 2000 (3500) years back (Baranowski 1977), the valley of the Werenskiold Glacier was free from ice and formed by fluvial processes and by litoral processes at its outlet. This is indicated by the remaining fossil tundra found in the front of the thawing glacier (Baranowski 1977) and also on the walls of the glacial cirque (Pękala 1980). It is difficult to determine now whether in the most recent glacial substage the maximum range of the Werenskiold Glacier coincided with the terminal moraine or reached beyond. Baranowski (private communication) belived that the Werenskiold Glacier went beyond the terminal moraine. It seems very probable that the terminal moraine of the Werenskiold Glacier does not mark the stopping period of this glacier but, rather, results from a change in the

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[2]) These wells were explored by speleologists from the Dąbrowa Basin Tatra Speleologist Club in 1979 and 1981. In August 1979 electric thermometers were set in the wall of the 39 m well.

regime of the glacier at a time when it "came upon land", as J. Jania suggests (1982). At present the Werenskiold Glacier undergoes intensive recession. Since 1958 the front of the glacier has retreated at an average annual rate of 20 m.

The geological structure of the basin of the Werenskiold Glacier is not fully known, in view of its being lergely covered by the glacial and slope sediments. According to K. Birkenmajer (1968) this area is built of proterozoic metamorphic rocks of the Hecla Hoek succession. These rocks belong to the Eimfjellet formation.

In the western part of the basin detailed investigations were performed by W. Smulikowski, which resulted in a 1:25000 geological map. This basin was also mapped by K. Birkenmajer[3]), and his unpublished map makes it possible to complement the knowledge of the geological structure in the eastern part of the basin. In the southern part of the basin quartizites, muscovite schists, gneisses and amphibolites dominate. The southern slopes of the valley of the Werenskiold Glacier are built of these rocks. The base of the glacier and the mountain ridges surrounding from east the valley of the Werenskiold are built alternately of crystalline schists mainly micaceous, quarzite schists with marble inserts and quartz-and -marble conglomerates. There are also numerous greenstone schists. The eastern part of the basin is built of the same rocks as those in the northern part, in which there is a good deal of marbles and quartizite and calcit schists.

3. Climate conditions

The climate conditions of the area of the Werenskiold Glacier were determined by the glaciological teams from Wrocław University who worked in Spitsbergen in 1957–60, 1970–75, and 1978–80. The basic meteorological elements were essentionally measured and registered in summer seasons, where the only yearly information dates from the period 1979/1980.

On the basis of the results of comparative analyses of meteorological data from the Polish Polar Station at Hornsund (Tables I and III) with information from the forefield of the Werenskiold Glacier, the magnitude and variation of the basic meteorogical elements can be taken as similar for both stations (Baranowski, Głowicki 1975; Pereyma, Piasecki 1982; Pereyma 1982).

The large area of the basin of the Werenskiold Glacier shows topoclimatological variations conditioned by orography, hypsometry and different bedrock.

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[3]) This is a 1:25000 map now being prepared for publication.

The radiation balance in the tundra zone of the Hornsund shore is positive in summer, i.e. about 20 kJ/cm^2 month in July and August. In the other seasons of the year it varies greatly, depending mostly on the presence of snow cover. In the glaciers of the region, among other things, as a result of their large albedo, the radiation balance decreases significantly in summer and takes a negative yearly value. For the forefield zone of the glaciers and tundra the annual total of the radiation balance is positive but close to zero.

A different system was found in the spatial distribution of the increase in the total radiation in the Hornsund area. The upper firn zones receive a slightly larger amount of this radiation, in summer months 3–5 kJ/cm^2 month on average, than the tundra seashore and the region of the ice forefield. This adventage in radiation access is caused by the significantly decreasing thickness of low clouds up the glaciers. These relations have been found in spite of the more stable position of cloud layers over the firn field of the Werenskiold Glacier with respect to its forefield or to Hornsund.

Table I.

The mean decade and monthly temperatures (t, °C) and relative humidities (U, %) of air in the basin of the Werenskiold Glacier and at Hornsund in August 1979.

	W		W_A		W_F		W_S		W_U		W_C		H	
	t	U	t	U	t	U	t	U	t	U	t	U	t	U
1—10	4.4	80	2.3	94	3.8	80	3.1	88	1.3	95	−0.1	96	3.2	86
11—20	7.9	81	6.1	91	5.9	85	4.7	90	3.5	100	4.4	93	5.1	88
21—31	3.3	75	0.9	89	2.5	78	1.5	87	−0.5	89	−0.6	93	2.9	76
1—31	5.2	79	3.0	91	4.0	81	3.0	88	1.4	99	1.2	94	3.7	83

W, W_A... W_C — meteorogical stations in the basin of the Werenskiold Glacier, located as in Fig. 1.

The mean air temperature in the forefield of the Werenskiold Glacier are slightly higher (1 to 2 °C) than those at Hornsund, in view of the greater effect of the processes of air foehnization in this region. In individual cases these differences can be considerable and reach about 10 °C.

In different zones of the basin of the Werenskiold Glacier it is possible to find the distinct dependence of the thermal relationships in the atmosphere on the effect of the surface of the glacier, which is greater than hypsometry may indicate. The variation in the spatial distribution of air temperature in the area of the glacier is largest in summer because of the lack of snow in part of the basin. This is illustrated by Table I which contains the mean values for August 1979.

A regular air temperature drop of 0.52°/100 m (August 1979) can be observed along the longitudinal profile of the glacier (W_S — W_U). In the upper part of the glacier it is possible to observe a gradual increase in the frequency of thermal investigations with large thickness. This is indicated by a gradient of 0.01 °C/100 m obtained for August 1979. The effect of this is the mean temperature similar for the firn field (W_U) and the nunatak (W_C) 300 m higher up.

In the light of the data obtained it is possible to evaluate the degree of the coaling effect of the glacier on the atmosphere in its vicinity. Under the conditions of summer in Spitsbergen it is 2.2 °C on average in the front zone and 1.6 °C in the middle zone.

The relative air humidity observed in the forefield of the Werenskiold Glacier (U, Table I) is on average lower than at Hornsund, which results from the greater dynamism of foehnization processes mentioned above. Higher relative humidities can be observed at stations being under the effect of the glacier, particularly in the firn field (W_U) which results from the damp air masses which stabilize there.

Irrespective of the differences in the average relationships between temperature and humidity found in the region, it should be noted that topoclimatological contrast increase in a circulation period which favours foehn processes, particularly in its initial phase, and in a period when cold masses of arctic air arrive. In the course of advection of warmer and damper masses of polar and sea air these contrasts decrease. According to the mean data obtained for Spitsbergen summer, the weather periods which favour the contrasts slightly exceed 50 per cent.

The precipitation noted in summer in the forefield of the Werenskiold Glacier is slightly smaller than at Hornsund, while its amount increases greatly on the surface of the glacier, reaching in the firn field a value twice as large as that of the total at Hornsund (Kosiba 1960, Baranowski 1968), and, in turn, the thickness of the winter snow cover is about there times as large. At the end of the winter seasons 1979/1980 the water equivalents of snow cover were, respectively, 1194 mm for the firn field, 700 mm for the middle part of glacier, 560 mm for the glacier front, 500 mm for the forefield and 317 mm for the plain part of the Fugleberget basin (Hornsund). On the glacier the length of the presence of the annual snow cover is longer from 1 to 3 months, depending on the altitude zone and partly on the orography, then that in the forefield and the tundra zone at Hornsund. Thus, the drainage of water from the basin of the glacier depends to a large extent on the progress in the disappearing of the snow cover in its area. According to the investigations in the summer of 1980 (Szczepankiewicz-Szmyrka 1981), the loss in the water balance caused by evaporation over the whole summer season in the area of the forefield of the Werenskiold Glacier can be evaluated as about 50–60 mm. For the zone of the tongue of the glacier the sum total of the loss caused by evaporation in the Spitsbergen summer can be about 20–30 mm. Taking into account the results of year-long measurements, it is possible to estimate the annual loss caused by evaporation as about 140 mm on average for the middle and lower parts of the basin of the Werenskiold Glacier.

4. A hydrological characterization

The basin of the Werenskiold Glacier is closed by a hydrometric profile set on the Glacier River at through break the terminal moraine. The river bed cuts here across a rock ledge, facilitating thus the selection of an appropriate place at which to set a limnigraph, water-level staffs and a profile for control discharge measurements. The first hydrometric profile with a limnigraph was installed in the summer of 1970 (Baranowski, Głowicki 1975). It was located in the upper part of the break, just below the point where the Glacial River joins the Angell River where it was used in the summer seasons of 1970–1974. In 1978 it was moved to the lower part of the breakthrough. In this position it was used in the summer seasons of 1978–1981 and throughout the hydrological year 1979/1980. With these profiles the whole drainage from the basin was controlled, since the Glacial River of the Werenskiold Glacier now is the only river which drains this area. In addition to the constant registration of water levels in the Glacial River, periodic flow measurements were taken in the most important undercurrents flowing from the glacier and a extensive programme of hydrological and hydrochemical investigations implemented. These investigations complemented the climatological programme (with 6 meteorological stations working in the basin) and the glaciological one (dynamism of ice movement, the magnitude of the surface ablation of the glacier, thermalkarst processes etc.). These investigations gave fullest data in 1972, 1973, 1979 and 1980.

Year-long investigations were carried out in the hydrological year 1979/1980, when water discharge was found also in the winter season. This water froze in the forefield of the glacier and measurements of the increment rate for this ice made it possible to determine the volume of this water Table II). The ice thawed in spring and became part of the spring outflow of the Glacial River.

The registration of water levels in the Glacial River was begun on 13 July, 1979 and ended on 13 November, 1979, a dozen or so days before the drainage from the basin stopped (25 November, 1979). In the spring of 1980 hydrological measurements were commenced when the drainage from the basin started, i.e. on 21 May, 1980. It was possible to begin registration of water levels as late as 14 July, 1980 and to carry it out until 5 September, 1980.

The results obtained in 1979/1980 permitted the distinguishing of hydro-

Table II.

Hydrological and hydrochemical characteristic of the polar hydrological year 1979/1980 in the basinof the Werenskiold Glacier

hydrological	number		Q*		q	T	ΔT	A		D		A —D		P	E	Q	P—Q
seasons	of days	m^3/s	mln m^3	mm	l/s km^2	mg/l	mg/l	m^3	m^3	m^3/km^2	m^3	m^3/km^2	%	mm	mm	mm	mm
summer 1979 22 July—27 August	37	7.6	24.4	558	175	44.9	27.4	436	266	5.1	170	3.9	39	50	30	560	−540
autumn 1979 28 August— 25 November	91	1.7	13.2	302	38	106.9	89.4	571	478	10.9	93	2.1	16	240	40	300	−100
winter 1979/1980 26 November 20 May	176	0.05	0.72	26	3	175.0	157.5	53	48	2.0	5	0.2	9		(700)**		
spring 1980 21 May— 22 July	63	5.6	30.5	696	128	61.6	44.1	751	538	12.3	213	4.9	28	90	30	700	+60
summer 1980 23 July— 3 September	43	10.3	38.4	878	236	47.8	30.3	732	464	10.6	268	6.1	37	300	30	880	−610
polar hydrological year 1979/1980 28 August— 3 September:	373	2.5	82.2	1876	58.2			2054	1480	33.8	574	13.1	28	1330	100	1880	−650

*) the symbols defined in formulae (1). (2) and (3).

**) the water reserve in snow determined at the end of the winter season.

logical seasons and the performance of a characterization of the polar hydrological year. The particular hydrological seasons were distinguished according to the analysis of the curve for the discharge (outflow) from the basin, taking into account the dominant water types feeding the basin in a given season. This differentiation of water types was assisted by an analysis of their chemical composition.

A short characterization of the hydrological seasons based on the data given in Table II in the present paper is given below.

The summer season of 1979 lasted 37 days, from 22 July to 27 August. It began when the rapid outflow of spring thaw water stopped. In the summer season the drainage consisted of water from thawed winter snow in the upper parts of the glacier, from thawing of the glacier and from rainfalls. The maximum water outflow, reaching 18 m^3/s came in the middle of August and was related to high air temperatures (above 13 °C) and rainfalls. The summer season ended with the conclusion of the intensive water outflow from the surface of the glacier. This season was characterized by large discharge. The mean outflow was 7.6 m^3/s, which suggests that this was among the seasons richest in water.

Table III.

The thermal seasons (distinction criteria, period and duration) in the area of the Hornsund Fiord in 1979 and 1980

season	t_x C	period	duration in days
summer 1979	$t_x \geqslant 2.5$	26 June — 31 August	67
		(22 July — 27 August)	(37)
autumn 1979	$-2.5 < t_i < 2.5$	1 September — 9 November	70
		(28 August — 25 November)	(91)
winter 1979/1980	$t_i \geqslant -2.5$	10 November — 19 May	191
		(26 November — 20 May)	(176)
spring 1980	$-2.5 < t_i < 2.5$	20 May — 18 June	29
		(21 May — 22 July)	(63)
summer 1980	$t_i \geqslant 2.5$	19 June — 1 September	73
		(23 July — 3 September)	(43)

The period and duration of the hydrological seasons in the basin of the Werenskiold Glacier are given in brackets

The autumn season of 1979 is one of the longest seasons of the polar hydrological year. It lasted 91 days, from 28 August to 25 November. It began when water from the inside of the glacier began to dominate in the outflow from the basin. This moment was very distinctly defined by an increase in the water mineralization. Over a dozen or so day at the beginning of the season it was possible to observe considerable discharge variations with relatively high maxima reaching 7 m^3/s. These variations are related to intensive rainfalls and relatively high air temperature. It is interesting to note a shift in the reaction time to a few days between the moment when the rainfall and high temperature occur and the increase in flow, in contrast to an almost immediate reaction in the summer season. The autumn season ended with the conclusion of the outflow from the basin. The mean outflow in the autumn season was low, i.e. 1.7 m^3/s. Over this period only twice as little water drained as in summer (13 mln m^3 versus 24 mln m^3).

The winter season 1979/1980 was the longest season of the polar hydrological year. It lasted 176 days, from 26 November, 1979 to 20 May, 1980. This season began with the conclusion of the outflow from the basin, while the water from the inside of the glacier froze in the form of naled ice and remained in the area of the internal ouwash. In this season only the water from the glacier flowed out down the Kvisla, the Glacier and the Angell Rivers. The total outflow by these ways decreased gradually from about 0.2 m^3/s at the beginning of the season to a dozen or so l/s at the end of winter. The mean seasonal outflow was estimated as 0.05 m^3/s. When recalculated for the glacier area this outflow was 26 mm (3 $l/s\ km^2$).

The water circulating inside the Werenskiold Glacier freezes in winter and only a slight amount of it leaves the glacier. In the course of freezing there is an increase in the mineralization of the remaining unfrozen water (the cryochemical effect). The discovery of the cryochemical effect (Pulina 1985) permited the calculation of the water this volume in the glacier at the beginning of the winter season. It was 3.6 mln m^3. Only 20 per cent, i.e. 0.7 mln m^3, of this volume drained, whereas the other part, 2.9 mln m^3, frozed within the glacier.

The winter season ends when the surface water from thawed winter snow and naleds in the forefield of the glacier starts. In turn, the water which froze in channels of the glacier drain only in the summer seasons. In the winter season snow, which is about 50 per cent of the annual precipitation total, gathers. The mean water reserve in snow was determined for the basin as about 700 mm.

The spring season of 1980 is the most dynamic season of the polar hydrological year. It began when the winter snow cover and naled ice began to thaw, i.e. in the second part of May (21 May) and continued until most snow water had flowed from the ablation part of the glacier, i.e. until the second part of July (22 July). Thus, the hydrological spring lasted 63 days and was twice as long as the thermal spring (Table II). In the unglaciated basins on the Hornsund Fiord the hydrological spring is shorter and closer to the thermal one.

In the first three weeks of the spring ablation water gathered in the Mewie Lake, as a result of the more difficult water outflow through the break in the terminal moraine, which was filled with winter snow. The retention effect of the lake caused the variation in the water outflow from the basin to be slight. The flow in this period varied from 0.5 to 2 m^3/s. In the second part of June there came a period of a rapid flow of thaw water caused by intensive rainfall (16 mm) and by a rapid increase in air temperature. The lack of registered water levels in this period (limnigraph being under snow) can partly be compensated for by the curve for the outflow from the Fugleberget basin where a similar spring regime was found[4]. It is probable that at that there were single water discharge of the order of 16–20 m^3/s. The season ends with lower flows slightly above 8 m^3/s. From incomplete data, the mean spring drainage was 5.6 m^3/s, which when recalculated for the basin area gives about 700 mm. These values are underestimated.

Compared to the summer of 1979, the summer season of 1980 was longer by a week (lasting 43 days) and richer in water (with a mean flow of 10.3 m^3/s — 878 mm), which was caused by a large amount of rainfall.

The polar hydrological year 1979/1980 lasted 373 days, from the beginning of autumn to the end of summer (28 August, 1973 — 3 September 1980). Over the 176 days of the winter season no water drained from and in its forefield. Thus, the water outflow from this basin lasted only half a year (197 days). The mean annual outflow from the basin was estimated as 2.5 m^3/s, which when recalculated for the basin area gives a water layer 876 mm thick. The unitary annual outflow was 58.2 $l/s\ km^2$. When recalculated for the time when the basin was actually drained, this gives values twice as large: with a flow rate of 48 m^3/s and unit discharge of 110 $l/s\ km^2$.

5. Physical and chemical properties of water

The chemical composition of the water of the Werenskiold Glacier was determined by the field laboratory of the expedition (Markowicz, Pulina 1979). Samples were taken above all from the Glacial River at the point where it breake through the terminal moraine (a hydrometric profile with a limnigraph). In addition samples were taken from all the tributaries of the Glacial River in the forefield of the Werenskiold Glacier. The determination was performed at the Glaciological Station on the Werenskiold Glacier and at the chemical laboratory of the Polish Polar Station at Hornsund.

The same methods as those for the Fugleberget basin were used here. They were described in the paper discussing the water balance and chemical denudation in this basin (Pulina, Krawczyk, Pereyma 1985).

In the autumn season of 1979 the mineralization of water increased

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[4] The curve of the spring water drainage from the basin of the Werenskiold Glacier will be completed when a statistical model of the drainage has been elaborated and verified with the results of measurements from the spring of 1982. Prior to this, the present paper gives values based on direct measurements.

from 51 to 133 mg/l. There was also an increase in the total hardness and the noncarbonate hardness caused mainly by chloride and sulphates of calcium and magnesium. The share of the noncarbonate hardness in the total hardness increased from 11 per cent to about 30 per cent. The pH values decreased from 7.6 to 7.0 to increase subsequently to 7.8 in the middle of November when the water mineralization was three times as high as in the summer season. The water type HCO^{-3} — Ca^{2+} — Mg^{2} dominated in autumn.

In the winter season 1979/1980 the water mineralization tended to increase further. There occurred maximum values of the mineralization, a few times as large as those for the summer water. The maximum value found on 9 April, 1980 was 1302.3 mg/l. The mean value for the whole season was 175 mg/l. There was also a large increase in the total and noncarbonate hardness. The share of the latter increased up to 35 per cent and as much as 40 per cent at the end of the season. A greater share of the ions $Na^{+}+K^{+}$ was found compared to the autumn waters. The pH values varied between 7.0—7.7. The water type HCO_3^- — Ca^{2+} — SO_4^{2-} dominated.

In the spring of 1980 the water mineralization decreased from 119 mg/l to 33 mg/l. The total and noncarbonate hardness also decreased. The share of the noncarbonate hardness, which was high (36 per cent) at the beginning of the season, subsequently decreased greatly and at the end of the season the total hardness was equal to the carbonate hardness. The pH values varied between 7.2—7.7. There was the water type HCO_3^- — Ca^{2+} — SO_4^{2-}, however, with a smaller share of the ions HCO_3^- and Ca^{2+} than in the previous seasons.

In the summer season of 1980 the water mineralization increased from 28 to 74 mg/l. The changes in the mineralization were strictly related to flow changes in the Glacial River. The total hardness increased only slightly, the share of the noncarbonate hardness was also small, up to 10 per cent. The pH values were relatively high, mainly over the range 7.5—7.7. The water type HCO_3^- — Ca^{2+} — $(Na^{+}+K^{+})$ occurred.

In the summer season of 1979 the physical and chemical properties were similar to the analogous season of 1980.

The hydrochemical investigations permit the following conclusions to be drawn:

1) In the course of the hydrological year water of a similar chemical type, the so-called bicarbonate—calcium water, circulates in the basin of the Werenskiold Glacier. This water shows some differentiation in terms of the magnitude of total mineralization and the share of the other cations and anions. A distinct increase in the noncarbonate hardness can be observed from the middle of autumn to the beginning of spring. This is related to an increase of the content of chlorides and sulphates of calcium and magnesium. In the spring water this increase results from the thawing

of naled ice and snow which has undergone the cryochemical process. In turn, it is difficult to explain the increase in the noncarbonate hardness from autumn to winter; it seems probable, however, that this is a result of the addition of snow and ice water which may not have had the opportunity of dissolving carbonate rocks, but has undergone the cryochemical process.

It follows from the above that the summer cycle water (with some share of the water from the end of spring and the early autumn)—which has participated in the process of dissolution of the bedrock particularly of carbonate rocks—and the water from the autumn-spring cycle—which has not had this possibility but undergone the cryochemical process–circulate in the basin.

2) The physical and chemical properties of the water were the additional criterion in distinguishing the hydrological seasons. A particularly determining factor was the magnitude of the total mineralization which permitted the boundaries between spring and summer and between summer and autumn to be determined.

6. Remarks on chemical denudation

The magnitude of chemical denudation in Spitsbergen was determined by some scholars for the unglaciated areas built of carbonate rocks (Corbel 1959, Hellden 1973). An extended study on this subject, including the chemical denudation of the areas built of metamorphic, noncarbonate rocks was published by one of the authors of this paper (Pulina 1974, 1977). It follows from these papers that chemical denudation in this area of the Arctic is relatively high and varies in carbonate rocks between 5 and 20 m^3/km^2 year. Some results of the hydrological investigations carried out in the unglaciated Fugleberget basin (the northern shore of the Hornsund Fiord), simulataneous with the investigations in the basin of the Werenskiold Glacier, were recently published (Pulina, Krawczyk, Pereyma 1985). This paper shows that the denudation of carbonate rocks which occur among insoluble metamorphic rocks is very high, reaching 50 m^3/km^2 year. The intensity of the denudation processes in this basin is additionally confirmed by the fact that this hight value is reached over only 5 months, since in the other part of the year, making up the winter season, the water does not circulate in this basin. The magnitude of chemical denudation in the basin of the Werenskiold Glacier, which is located in a geological area similar to that of the Fugleberget basin, but which, in contrast, is covered by the glacier is given below.

The magnitude of chemical denudation was determined by hydrometric and hydrochemical methods proposed by one of the authors (Pulina 1974). Calculations were made according to the formula

(1) $$D = 0.0126 \cdot \Delta T \cdot q; \ \Delta T = T - T_a,$$

where D is the chemical denudation, in m^3/km^2 year or in mm/1000 years; 0.0126 is a recalculation factor; ΔT is the water mineralization due to the dissolution of rocks in the basin, in mg/l; T is the water mineralization found in the basin; T_a is the mineralization of allochthonic water, precipitation water in this case; and q is the unit dischange, in $l/s\ km^2$. The above values are given in the form of the annual means.

The magnitude of the ionic run-off in the particular seasons was determined from formula (2), which results from a modification of formula (1).

(2) $$A_m = 0.03456 \cdot T \cdot Q \cdot t$$

where A_m is the ionic run-off, in m^3, recalculated to the number of days designated by the symbol t; T is the water mineralization found in the basin, in mg/l; and Q is the water discharge in a time t, in m^3/s.

Formula (2) also permits the calculation of the denudation of the whole basin, but in this case the value T must be replaced by the value ΔT. This formula takes the form

(3) $$D_m = 0.03456 \cdot \Delta T \cdot Q \cdot t$$

The particular parameters included in the above formulae, recalculated for the basin of the Werenskiold Glacier, are given in Table II. These values are related both to the whole polar hydrological year 1979/1980 and to its individual seasons.

The above data permit the following conclusions to be drawn regarding the magnitude of chemical denudation in the glaciated basin of the Werenskiold Glacier.

The magnitude of chemical denudation is 33.8 m^3/km^2 year, which when recalculated for the whole basin area gives 1480 m^3/year. The strongest denudation, 12.3 m^3/km^2, occurs in spring. Denudation in summer and autumn is similar, i.e. 10.6 versus 10.9 m^3/km^2. The water circulating in winter in the Werenskiold Glacier eliminates 48 m^3 of dissolved rock from the glacier, which when recalculated for a unit area of 1 km^2 gives 2 m^3.

A relatively large amount of salts, which came down with precipitations, was found in the basin. This amount was defined as 13.1 m^3/km^2 year, which when recalculated for the basin area gives 574 m^3/year. The largest amount of salts falls in summer (268 m^3) and spring (213 m^3). In the summer season these salt mainly come from thawed glacial ice.

The above values of chemical denudation apply to the whole basin and not only to this part of it which is glacier-covered and covers 64 per cent of the area. Therefore, it seems purposeful to stress that chemical denudation is greater in the glaciated area than in the unglaciated forefield of the glacier through which transitory glacial water flows. The data obtained permit these two area to be distinguished and the magnitude of denudation to be calculated for each. This will be the subject of another paper. There also remains the problem of those rocks which are most strongly affected by the denudation processes. These are certainly carbonate rocks (marbles and calcites which occur among insoluble rocks). This is indicated by the ionic composition of the water leaving the basin. In view of the slight propagation of these rocks in the basin, the real magnitude of chemical denudation of them is several times as great and may reach 100 m^3/km^2 year.

7. Some elements of the water and denudation balance

The data presented in this paper are an exception among the ample but fragmentary hydrological materials on Spitsbergen. On the basis of year-long investigations, an attempt was undertaken to determine the elements of a shorter water balance in the glaciated basin of the Werenskiold Glacier. These calculations also permitted an annual balance of chemical denudation to be presented. Table II show the elements which were included in the annual water and denudation balance.

Here is an interpretation of the results obtained. A negative water balance was found in the glaciated basin of the Werenskiold Glacier. In the hydrological year under study 650 mm (28 mln m^3) more water flowed from this basin that it obtained from precipitation. The additional water came from the thawing of the Werenskiold Glacier and to a small extent also from long-term snow. It is the measure of the intensity of the ablation of the glacier which is in stage of deep recession. The value given here, which applies to the annual ablation of the glacier and is 35 per cent of the whole drainage from the basin, is underestimated, since it was calculated for the whole area of the basin, while the glacier covers only 64 per cent of it. Analysis of the values of the balance in particular hydrological seasons shows that the most intensive ablation of the glacier occurs in summer and partly in autumn.

It is interesting to note the large water volume circulating in the basin, i.e. 1876 mm (58,2 $l/s\,km^2$). 84 per cent of this water (157 mm) flows out in the spring and summer seasons. This is mainly water from thawed winter snow and glacier, with a small share of precipitation water (330 mm), i.e. only 21 per cent. The large discharge in these seasons is confirmed by the large values of q, 128 and 236 $l/s\,km^2$. The winter season is not included in the water balance (because of the lack of outflow from the basin), but still at that time water moves in the channels of the glacier. The autflow from the glacier consists then of water from the summer and autumn reserve, to the amount of 0.72 mln m^3 (3 $l/s\,km^2$).

In analyzing the elements of the water balance, it is interesting to note the relatively small amont of water from precipitation in spring summer and autumn (530 mm). It is thus necessary to stress the large role of the water from winter snow (700 mm) which constitutes almost 60 per cent of all precipitation water circulating in the basin under study. In view of the fact that in that hydrological year the summer percipitation was relatively high (300 mm) compared, for example, to the previous summer (50 mm), a still smaller rainfall, with respect to winter snow precipitation, should be expected in dry summers.

Regarding, in turn, the results of the chemical denudation balance, a large volume of salts drained from the basin, i.e. 46.9 m^3/km^2 year (2054 m^3/year), can be found. Within this volume, 28 per cent of the salts comes from precipitation (13.1 m^3/km^2 year) and only 72 per cent (33.8 m^3/km^2 year) is the real olume of denuded rock. This fact is confirmed by the following proportions: within 82.2 mln m^3 of water (1876 mm) flowing over the year from the basin of the Werenskiold Glacier there is 2054 m^3 of dissolved salts, 72 per cent of which, i.e. 1480 m^3, comers from the dissolution of rocks in the basin.

8. Conclusions

The basin of the Werenskiold Glacier represent well the glaciated areas of the shore and the coastal mountains in Spitsbergen. Similar basins are quite common in the coastal mountains in Spitsbergen. The lower part of these basins is closed by a bank of terminal moraines situated near the seashore, is usually free from ice and represents stages of the recent presence presence of the glacier, which is now in a state of deep recession. Some of the glaciers have lost contact with the ice cup in the central part of the island and, like the Werenskiold Glacier, have transformed into glaciers of the Alpine type. The minority of the other glaciers still reach up to the central part and are fed from the central firn field, whereby the degree of their recessions is smaller compared to the former basins.

The main subject of the present paper is the water regime of the glaciated valley shaped by the recessions of the glacier. This fact is reflected by the negative water balance. The basin lives at the expense of the thawing glacier. Another dominant characteristic of this basin is the immense hydrological contrast between the particularly active spring and autumn half-year and the almost dead winter half of the hydrological year.

9. Резюме

Даны результаты гидрологических и гидрохимических исследований, проведенных в бассейне ледника Вереншельда, с учетом решающих климатических элементов. Пред-

ставлены также избранные элементы водного балланса и баланса массы, определенные на основании исследований, проведенных в течение всего полярного гидрологического года 1979—1980.

10. Streszczenie

Artykuł zawiera wyniki badań hydrologicznych i hydrochemicznych przeprowadzonych w zlewni Lodowca Werenskiolda, na tle decydujących elementów klimatycznych. Przedstawiono również wybrane elementy bilansu wodnego i bilansu masy określone na podstawie całorocznych badań w polarnym roku hydrologicznym 1979—1980.

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