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Hydrological Data-Model Work in Greenland

Th. Thomsen and G.H. Jørgensen

Greenland Technical Organization,
Copenhagen, Denmark

The hydrological studies of the Greenland technical Organization in Greenland are being followed up at Copenhagen by hydrological data work as well as hydrological model-simulation.

The hydrological regions vary greatly in Greenland, depending on whether the drainage basin is influenced by ablation runoff. To describe a runoff time series from these areas, a hydrological model calibration is made, followed by a simulation. In drainage basins influenced by rain and snow only, a slightly modified version of the precipitation runoff model (NAM) is applied. The parameter transfer for the determination of model input is found by intensive data analysis work here between Nuuk and Kangerluarsunnguup Tasersua (KANG) for temperature and precipitation along with detailed investigations in the basin. This is to ensure that a too short calibration period in connection with the adaption of a hydrological model to the basin data is balanced in the manner that these adapt the hydrological model, and not vice versa.

In drainage basins also influenced by ablation runoff it is not possible to use a traditional precipitation runoff model but a hydrological ablation model has been developed in cooperation with The Geological Survey of Greenland. The hydrological ablation model describes the transfer of the temperature after heating and cooling factors as well as snow mobility on the ice, melting density criteria, refreezing etc. The model has been applied to the hydrological basin of Paakitsup Akuliarusersua (PAKI) at Ilulissat where 90% of the drainage basin is covered by the Ice cap.

Data evaluation work prior to hydrological model calibration thus allows for a higher degree of simulation reliability.

Introduction

Today, hydrological studies are made in 17 different basins in Greenland, see Fig. 1, at varying intensities depending on the basin appearance and location. The automatic hydro-meteorologic stations in the basins described by T. Thomsen (1983 c) are used as bases for the later hydrological calculations and are placed around the existing urban communities in areas of major hydrological potentials.

In relation to hydro power, the hydrological studies primarily aim at providing long time series of the essential parameters. This may be done over a protracted period of time in determining these parameters (incl., among others, runoff, precipitation, and temperature) at the automatic stations. Long periods of time are not available for the Greenlandic projects calling for results within a few years.

In order to provide a hydrological basis applicable to-day, the data collection from the automatic stations of which a few have transmission through satellites is combined with more intensive hydrological measurements at the basins. This is done with a view to establish already now optimal reliability of the hydrological background.

A long time series is then made by running a hydrological model. Traditional precipitation runoff models are so advanced today that any further improvements may only be generated by comprehensive data analysis work prior to the model calibration. These assumptions apply only to drainage basins where the runoff depends on precipitation alone. In drainage basins where the runoff also depends on ablation from the Ice cap, it is not possible to apply a traditional precipitation runoff model since it does neither describe the heating/cooling factors, nor the density criteria, refreezing etc.

Hydrological Localities

In connection with the hydrological hydro power studies at Nuuk, a hydrological data parameter analysis with subsequent model simulation was performed at the basin of the KANG using an extended version of the NAM model which has been adapted to the current data basis as well as to the specific conditions in Greenland.

The application of a traditional precipitation runoff model is due to the fact that the runoff conditions are caused by precipitation with 2 % of local glaciers. The drainage basin is 582 km^2 out of which the main lake covers 75 km^2 located 250 m a.s.l. The total lake percentage of the drainage basin is appr. 15%. The mean hypsographic level of the basin is 680 m, the max. level being up to 1,600 m a.s.l.

In performing the hydrological work at Ilulissat it has not been possible to apply a hydrological data parameter analysis directly since the runoff conditions are primarily described by the ablation from the Ice cap. Consequently, a hydrological

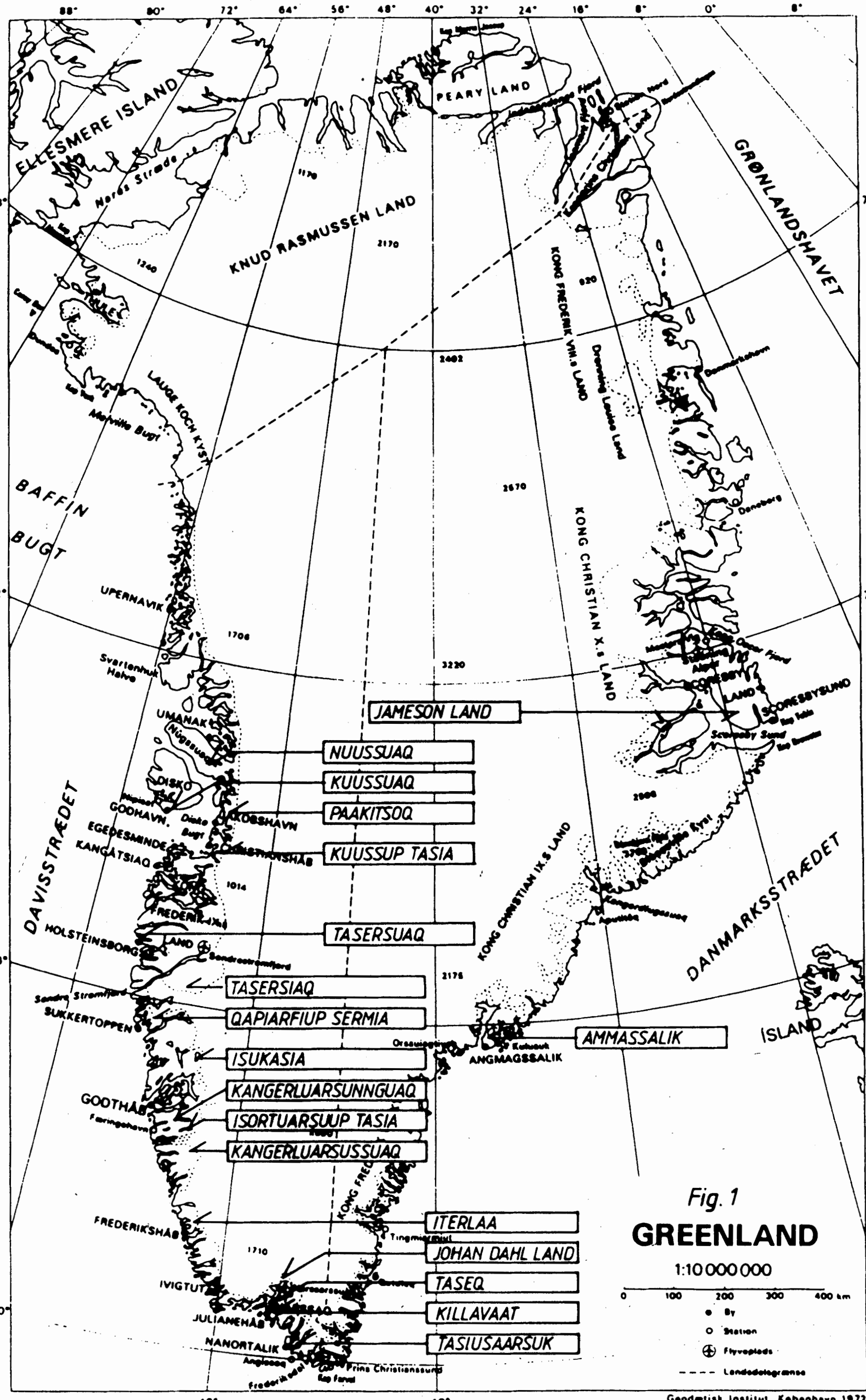

Fig. 1. Hydrological studies in Greenland.

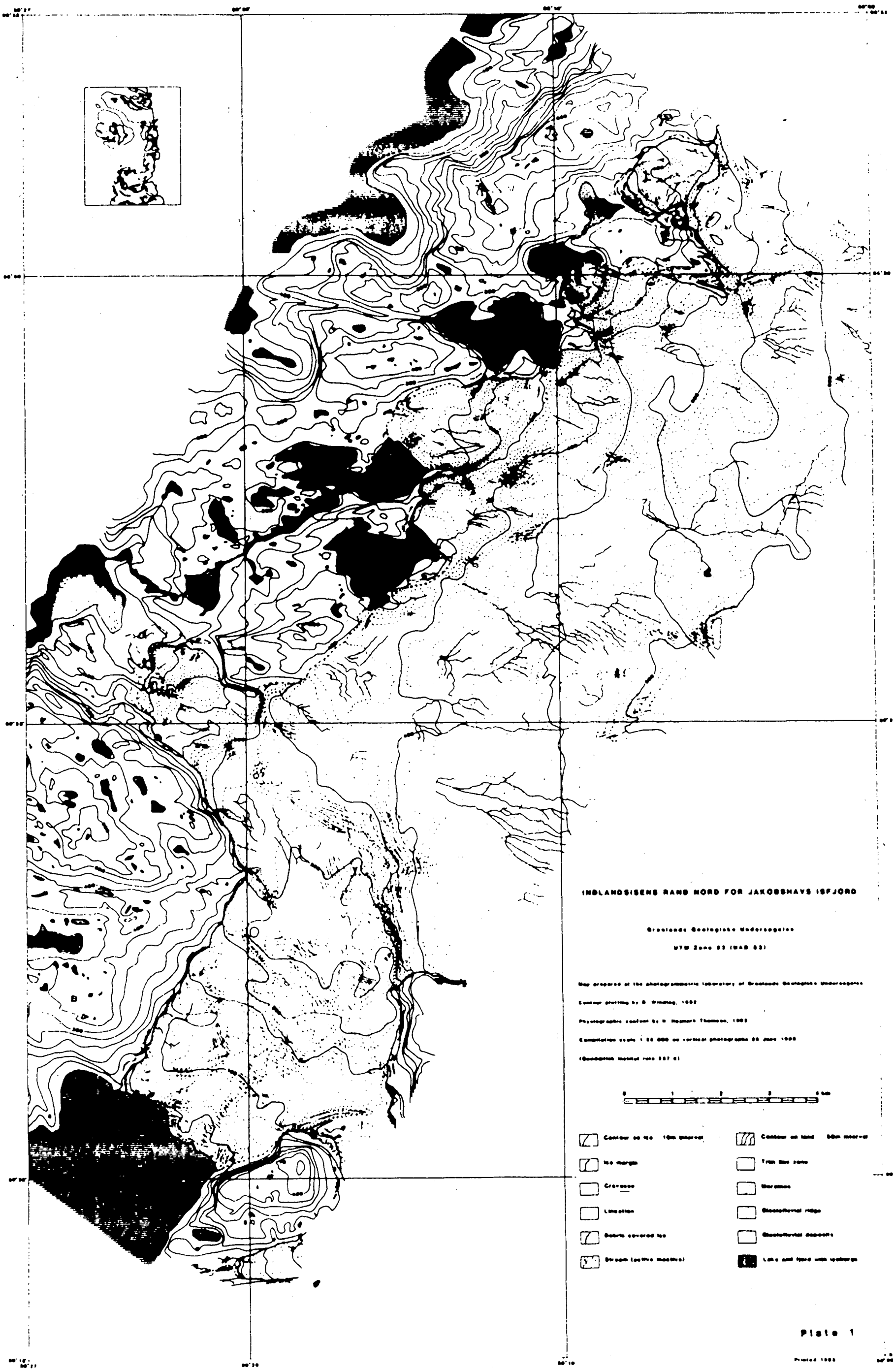

Fig. 2. Drainage basin at Paakitsup Akuliarusersua.

ablation model has been developed; over the ice-free area, this is a traditional precipitation runoff model which includes only the most primary magazines contributing to the runoff. On the Ice cap, the ablation is described by drainage basin based on a satellite pictures, ice melting by heating/cooling factors and refreezing depending on density requirements specified.

The ice-free drainage basin PAKI is 33 km^2 whereas the ice-covered drainage basin is 265 km^2. The mean height of the entire basin is 1,050 m above mean sea level whereas the main lake lies at a level of 187 m, Fig. 2.

Hydrological Data Basis

The hydrological data basis at KANG is based on measurements in the basin (automatically and manually) and on the basis of registrations made by the Meteorological Institute (MI) at Nuuk. The crucial factors of the model work integrated in the data parameter analysis are those of temperature and precipitation.

For evaluation of precipitation distribution in the KANG basin in the form of rain, data have been used from precipitation totalizators in three representative lines in the basin (Fig. 3).

It appears from Fig. 3 that the precipitation on the local glacier at the north western part of the basin is about twice as high as the precipitation at the automatic station 422 at the eastern part of the basin. Precipitation basin average comes to 130% of the precipitation at station 422 at lake level. Tabel 1 shows that the precipitation basin average in the form of rain has been 55% of the precipitation at Nuuk. On the basis of a mean level of the basin of 680 m, this comes out as a mean precipitation growth of 7% per 100 m. Fig. 3 also shows that the west-eastern precipitation gradient is not dominating within the drainage basin.

For determination of the winter precipitation no actual snow evaluation has been made (merely scattered point measurements).

Application of water level registration in the basin enables the determination of the winter precipitation. Fig. 4 shows that snowfall on the lake ice will cause the surface to raise and thus also a pressure rise measured by the pressure transducer, generating increased runoff from the lake. Since the lake ice constitutes a com-

Tabel 1. – Precipitation distribution at KANG

Period	Station 422 Registr.	130 %	Nuuk (MI)
21.06.-20.08.1981	92 mm	122 mm	230 mm
19.06.-30.08.1982	69 mm	90 mm	151 mm

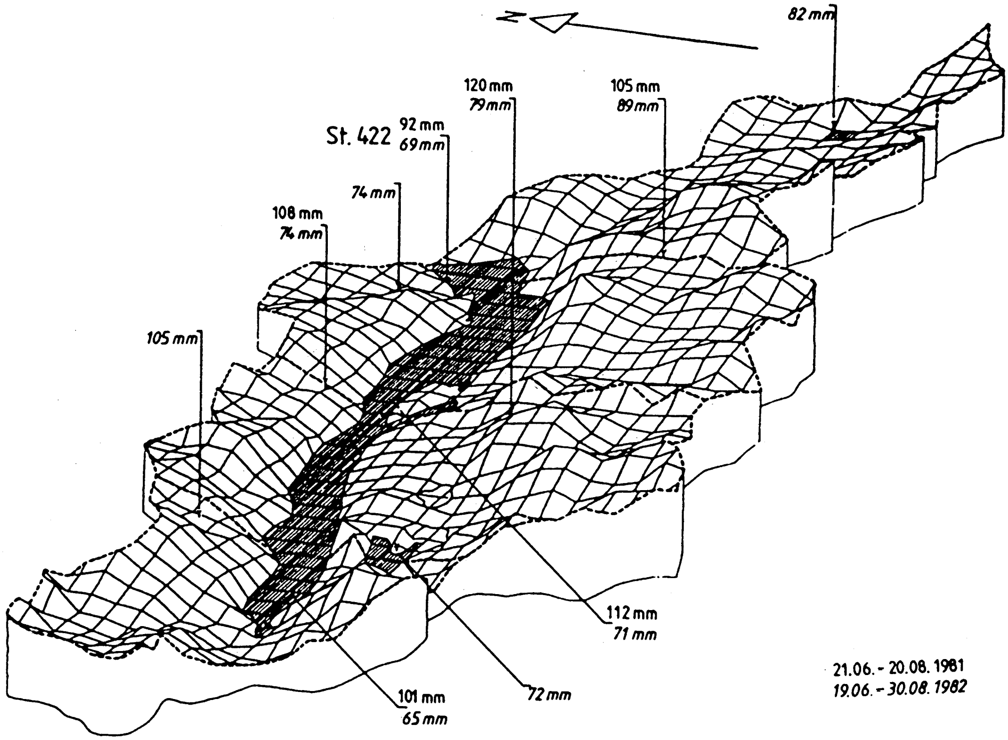

Fig. 3. Precipitation totalizators for determination of rain distribution.

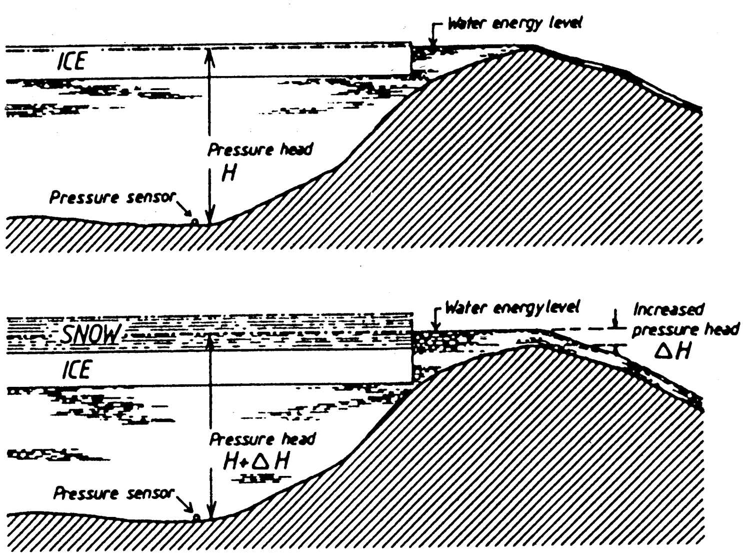

Fig. 4. Registration of snow precipitation.

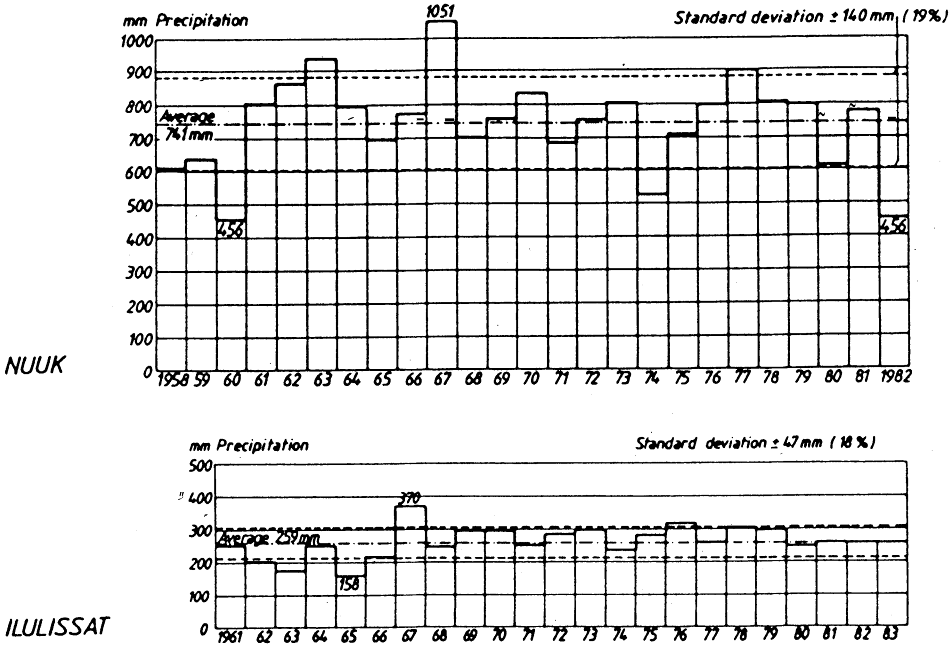

Fig. 5. Precipitation measurements at Nuuk and Ilulissat.

plete plastic body and is thus not affected by any marginal effect, the runoff from the lake may be equalled to the weight of the superposed snow volume in water equivalent value. The increased pressure head on the lake due to snowfall measured is thus a measure of the snow precipitation. If the continuity-equation is established for the lake, and the accession during the precipitation event is fixed equal to zero, the snow precipitation may be determined by

$$Q \equiv I + \frac{dH}{dt} A_L \qquad (1)$$

where I is the snow precipitation.

For the winter period at KANG from 10th October, 1981, to 10th May, 1982, incorporated in the model calibration period, altogether 165 mm of water equivalent snow was registered at the lake by applying the method shown in Fig. 4.

Fig. 5 shows the distribution of the annual precipitation at the Meteorological Institute at Nuuk and Ilulissat which is used for the model simulation. It appears from the figure that the mean annual precipitation at Nuuk for the period 1958-1982 is 740 mm, showing one standard deviation of 140 mm (19 %), and at Ilulissat for the period 1961-1983 is 259 mm, showing one standard deviation of 47 mm (18 %).

The precipitation series are found to be without any significant long-term trend.

The annual precipitation data stated in Fig. 5 are non-corrected precipitation

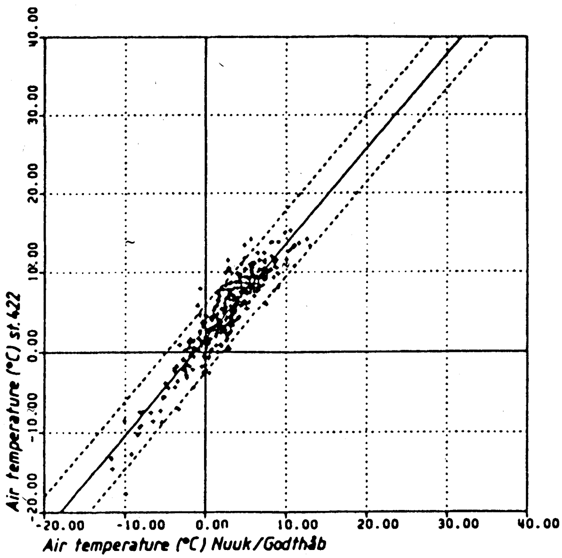

Fig. 6. Comparison of temperatures between Nuuk and station 422 (april-september).

observations. For determination of the actual precipitation, previous model simulations, conducted by Greenland technical Organization, from Nanortalik and Narsaq show that the measurements made by the Meteorological Institute should be corrected using a factor of appr. 1.15 for summer precipitation (rain) and another factor of 1.50-1.75 for winter precipitation (snow).

Previous model descriptions often assume a uniform annual distribution of temperature conditions between »town« and »basin«. In respect of conditions in Greenland, it turns out that the air temperature in the »basin« is lower in wintertime and higher in summertime that in the nearest »town«. Dates of separation for the two temperature gradients are generally very well defined but may possibly in relation to models be made dynamic as a fixed separation temperature in the »town/basin«. Today, this is not possible to include in some models. In the hydrological ablation model, this aspect has been determined partly by a heating factor where temperature is transferred from the coastal town to the Ice cap edge in the basin. The temperature is then transferred to the drainage ice area after a temperature cooling gradient.

It is obvious that the temperature data during the melting period are the interesting ones, and not, for instance, winter extremes. Fig. 6 shows a comparison of the 24-hour mean temperatures during the period of April-September for 1981 and 1982. The regression line has been worked out at

$$T_{422} \equiv 1.20\, T_{\text{Nuuk}} + 1.69 \qquad (2)$$

$$r^2 = 0.92 \qquad (3)$$

Temperature analyses for the entire year also show that the temperature at station 422 shows higher absolute fluctuations than at Nuuk which is influenced by its coastal climate. This may influence the subsequent data adaption in connection with the model calibration.

In respect of the PAKI basin, similar detailed data work cannot be done since the basis is non-existent. The hydrological ablation model has, in respect of the ablation part alone, been calibrated against ablation changes measured before and after the 1983 melting season, respectively.

For the calibration of the hydrological model, a runoff series measured from the outlet of the drainage basin has been used. The runoff from major precipitation areas which are affected by precipitation in the form of rain and snow only is, like in the minor areas, characterized by the snow melting. For the KANG basin, this water volume is so large that precipitation in the form of rain during the melting period running throughout the summer does not show on the hydrograph. The recession runoff does not decline as fast after runoff maximum as in minor precipitation basins which is partly due to a delay through the large lake system.

The hydrological regime for drainage basins affected by ablation are by way of runoff, described by its size, here PAKI at Ilulissat. In addition to a slightly decreasing recession part, the hydrograph is characterized by a more even rise in the beginning of the melting season. During the summer period, precipitation events over the basin, emptying of ice-dam lakes or cold periods are shown in part as local peaks or local dips in the hydrograph. For the traditional description of the particular component parts in the general appearance of the hydrograph refer to Dunne and Leopold (1978), among others.

Using these parameter descriptions it is then possible to set up a data file and try to find that the water balance fits within a certain number of percent. Using this data analysis, you avoid a simulation fault deriving from a too brief calibration period where it is possible using various parameter combinations in the calibration file to describe the runoff. Too brief calibration periods, i.e. less that 7 to 10 years of measurements, will occur in the case of all pre-projectings in Greenland.

Hydrological Model Description

The hydrological model applied will depend on the runoff conditions of the basin. In respect of hydrological basins in Greenland, it is not possible to use the same model type when the runoff is influenced by ablation from the Ice cap or from greater local glaciers in the drainage basin.

The hydrological model applied in drainage basins only with smaller local glaciers is a modified version of the traditional NAM model, described by Nielsen and Hansen (1973).

The modification of the model in comparison with previous work by Gottlieb (1980) covers primarily the routing through a lake storage where the runoff is made in relation to a known Q-H relation. The model descriptions relating to snow and rain in the basin are generally the same, however, precipitation on the lake storage is not stored since it would cause an immediate runoff increase. The

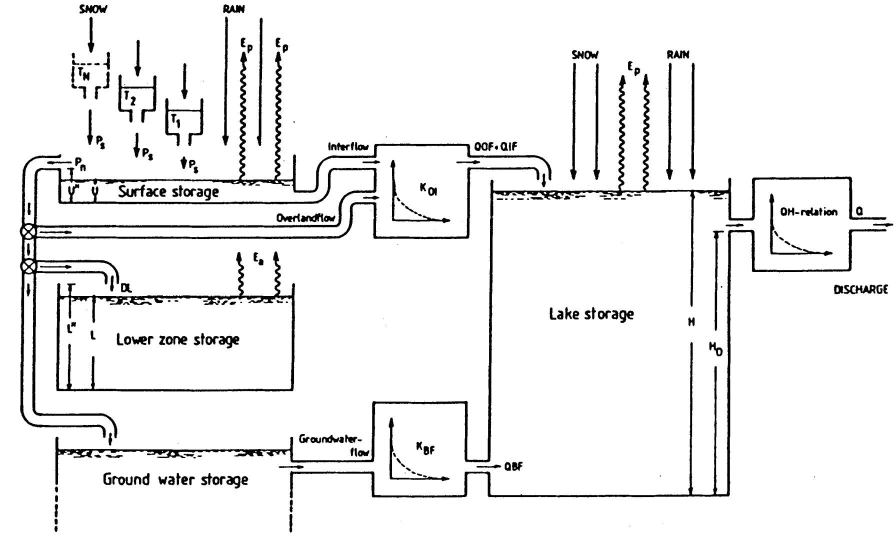

Fig. 7. Adapted NAM model structure.

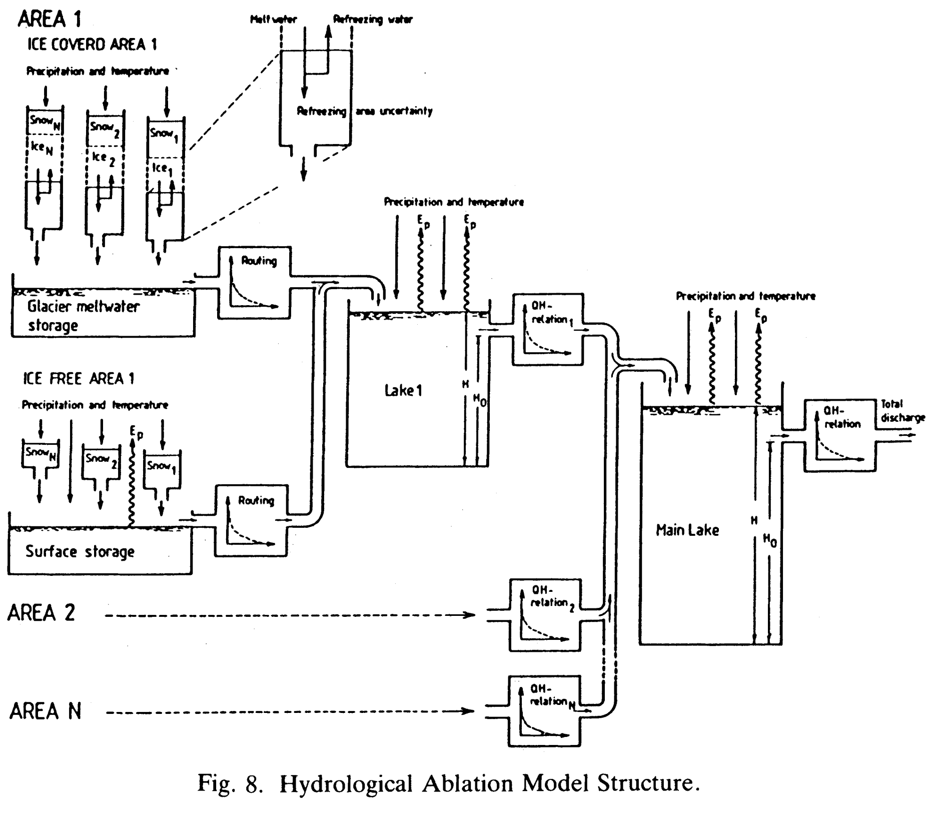

Fig. 8. Hydrological Ablation Model Structure.

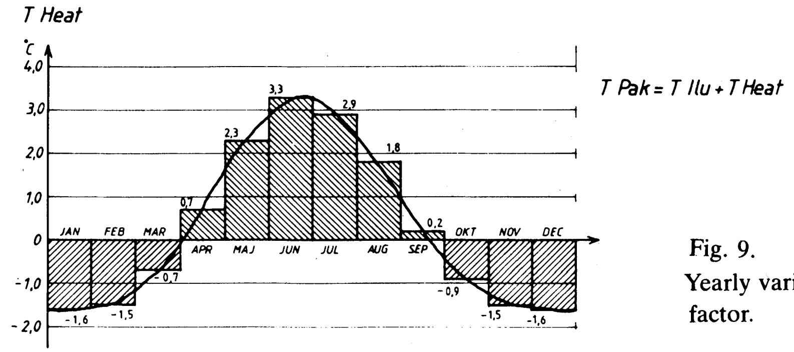

Fig. 9.
Yearly variation of heating factor.

actual snow melting is made as usual from a timevariant degree day factor.

The final model structure appears from Fig. 7.

The hydrological ablation model consists of two parts, a model description of the ice-covered area, and a model description of the ice-free area. Routing-wise, the model description of the ice-covered area has been described as a traditional precipitation runoff model, the routing through the ice reservoir being a linear reservoir, the drainage basin on the Ice cap being sub-divided depending on the density of ablation measurements. The model is calibrated on the spot iteratively where primarily the routing of ablation water volumes determines the value of calibration parameters. The temperature gradient to the basin ice edge (the heating factor) has been determined by measurements made by The Geological Survey of Greenland at Qamannasuup Sermia east of Nuuk (personal communication). The absolute size of the heating factor has been distributed on an annual basis, as a function of the short-wave radiation and calibrated on the spot at absolute ablation and cooling gradient values measured, see Fig. 9.

The temperature transfer over the Ice has been described by a cooling gradient, the temperature gradient over an ice-covered area being highly different from the temperature gradient over an ice-free area. The drainage basin borders over the Ice cap have been determined by local knowledge and by satellite picture drawings, H. H. Thomsen (1983 b).

Model Calibration

A detailed parameter description of the transfer to the particular areas will vary for drainage basin without ablation from the Ice cap to drainage basin with ablation. Since the ablation generally constitutes a very large total water volume of runoff, it is most reasonable to consider the parameter transfer to the Ice cap.

When performing the data analysis work relating to the basin without any appreciable ablation influence and to the Ice cap for basins primarily dominated by ablation, it is possible to get a good calibration since all significant model parameters have been determined in advance.

Table 2 – Model Parameters and Model Corrections.

Drainage Basin: Kang (Nuuk)

	a.s.l. (m)	Area (km^2)	Temp.cor. (°C)	Prec.cor. (+ % of 422)
Lake KANG	250	75	0.0	0
	250-500	120	−0.6	+15
	500-750	135	−2.0	+25
	750-1000	155	−3.0	+40
	1000-	85	−5.0	+60
Gletscher	1250	12	−5.0	+80

Storage capacities	$U^* = 1$ mm
	$L^* = 40$ mm
Overflow discharge	$C_{OF} = 0.4$
	$C_{L2} = 0.0$
Interflow	$C_{IF} = 0.05$
	$C_{LI} = 0.0$
Ground water flow	$C_{LG} = 0.0$
Time routing factor	$K_{OI} = 1.4$ day
	$K_{BF} = 26$ days
Q-H relation	$H_O = 96.50$ m
	$A = 11.85$
	$B = 2.30$
Snow-routing	Changing temperature rain/snow 0°C
	Melt-temperature 0°C
	Time-dependent degree day factor
	2.4 mm/°C/day.
	Time-indenpendent degree-day factor
	0.0 mm/°C/day.
	Lower limit for total drainage basin covering 150 mm.
Corrections	Temperature transfer
	$T_{422} = 1{,}20 \times T_{NUUK} + 1.69$
	Precipitation transfer
	$P_{422} = 0.40 \times P_{NUUK}$
	Precipitation correction (rain) 1.15
	Additional snow correction 1.74

cont.

Table 2 shows the conditions relating to the hydrological model runs.

The two hydrological models have been calibrated using two years of measurements in 1981 and 1982 from KANG at Nuuk and four years of measurements in 1980 to 1983 for PAKI at Ilulissat, respectively, however, ablation measurements have been made during one season only, that of 1983.

Table 2 – cont.

Drainage Basin: Paki (Ilulissat)

	a.s.l. (m)	Area (km²)			Temp.cor. (°C)	Prec.cor. (+ of JAK)	
Ice-free	<200	0*	4.8**	0***	−0.6	−30	
	200-400	11.4	6.8	3.5	−1.8	−20	
	400-600	6.0	0	0	−3.0	−10	
	600-800	0.3	0	0	−4.2	0	
						Summer/Winter	
Ice area	<200	0*	0.3**	0***	−0.6	−30	−100
	200-400	2.3	22.8**	2.3***	−1.8	−20	−100
	400-600	15.2	~11.3	6.7***	−3.0	−10	− 60
	600-800	16.4	13.2	5.3	−4.2	0	− 20
	800-1000	23.2	8.3	5.3	−5.4	+10	+ 20
	1000-1200	16.7	9.8	8.9	−6.6	+20	+ 40
	1200-1400	16.7	10.9	9.7	−7.8	+15	+ 30
	1400-1600	15.2	10.2	9.5	−9.0	+10	+ 20
	1600-1800	14.4	11.8	9.8	−10.2	+ 5	+ 10

* Drainage basin to lake system 233
** Drainage basin to lake system 187
*** Drainage basin to lake system 323

Ice-free conditions

Time routing	$K_{OI} \equiv 1$ day
	$K_{GF} \equiv 2{,}5$ day
Q-H relation	$H_O \equiv 96.98$ m
	$A = 11.41$
	$B = 2.74$
Snow and ice routing:	Changing temperature rain/snow 0°C Melttemperatur 0°C Time independent degree-day factor 6.3 mm/°C/day. Lower limit for total drainage basin covering 300 mm. Reefreezing snow on ice: while density increases from 0.3 to 0.9. Snown in ice-free: while density increases from 0.3 to 0.5. Ice black box: −2.5 %.
Corrections	Temperature transfer: $T_{\text{icefree}} \equiv T_{\text{Ilul}} + T_{\text{Heat}}$ $T_{\text{ice}} = T_{\text{icefree}} \times 0.83 - 0.7$°C. Precipitation correction (rain) 1.15 Additional snow correction 1.50.

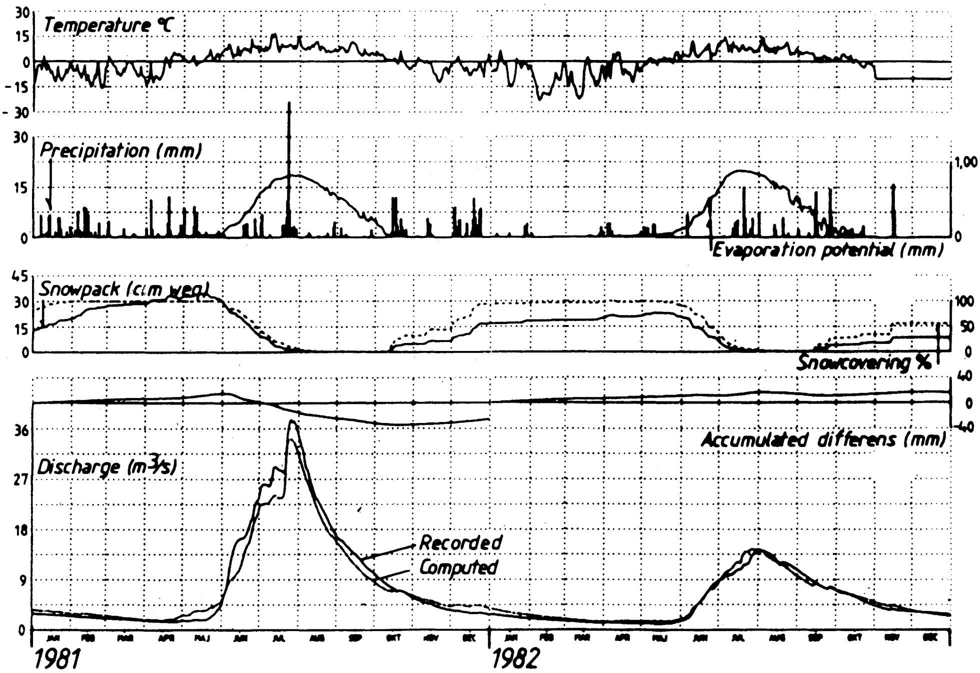

Fig. 10. Comparison between streamflow recorded and simulated calculated using adapted version of NAM at Kangerluarsunnguup Tasersua.

The runoff from KANG varies greatly from 1981 to 1982, i.e. from 287 million m^3 to 151 million m^3, thus enabling the testing of the probability of the parameter determinations assumed under the particular varying conditions. By transfer of the precipitation and the temperature from Nuuk at values shown in Table 2, the connection between the runoff measured and simulated is obtained, as shown in Fig. 10.

The modified NAM model was calibrated at r^2 = 0.986 on a 24-hour basis. At the same time, the water balance between the runoff measured and the one simulated has almost been met since in 1981 there is a deficit of 6 % and in 1982 a surplus of 7 % of the annual runoff. A simulation of the annual runoff has then been made for the period of 1959-1982. The mean annual runoff for this period is 250 million m^3, with one standard deviation of ± 25 %. On the basis of a two-year calibration basis, it is not possible to calculate the effectiveness of the period of time simulated.

The calibration of the hydrological ablation model has been made using the annual runoff and the ablation measured, too, H. H. Thomsen (1983a). The annual runoff measured for PAKI and the values calibrated are stated in Table 3.

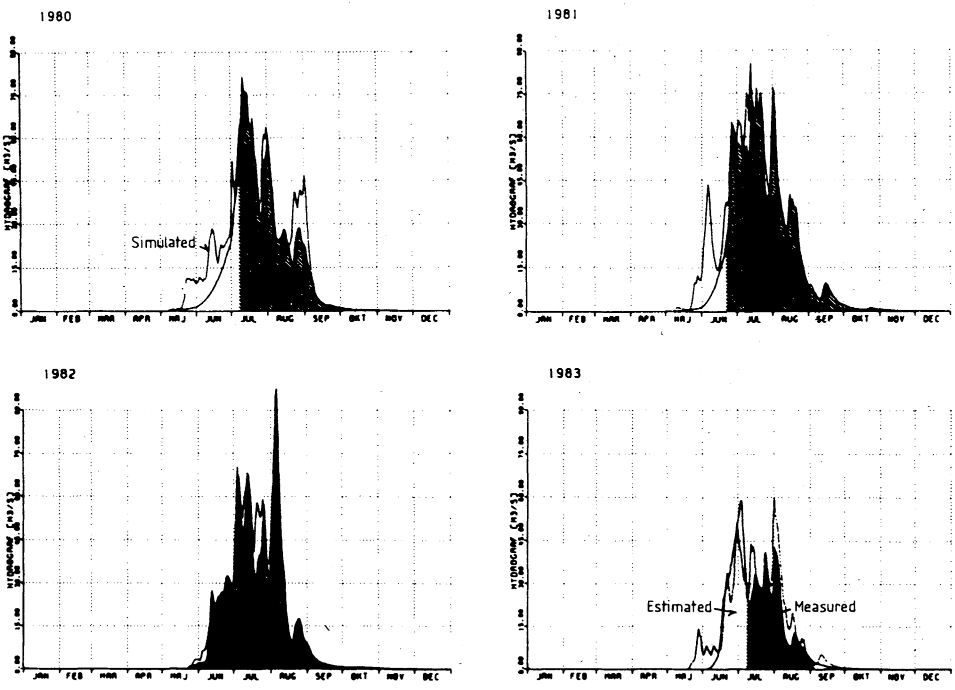

Fig. 11. Simulated runoff – using Hydrological Ablation Model at Paakitsup Akuliarusersua.

Table 3 – Runoff Values at PAKI 1980-1983 (all figures in million m^3)

	Runoff Measured	From this Estimated	Runoff Simulated	Runoff Difference
1980	316	89	312	+ 4
1981	361	55	354	+ 9
1982	277	1	268	+ 9
1983	185	85	204	– 10
Mean	285 ± 74		285 ± 64	

The calibration result appears from Fig. 11. A simulation of the annual runoff was then made for 1961-1983 for which the hydrological ablation model was applied to the drainage basin on the Ice cap, and a traditional hydrological runoff model was applied to the ice-free drainage basin. If the runoff simulated is applied as a runoff measured during the periods in which these have been estimated, see Figure 11, you will get a correlation coefficient for the annual runoff of $r^2 = 0.989$.

Future Model Development

For improved future application of the hydrological model tool the model work uncertainty deriving from uncertain and non-processed application of input data will have to be improved. Thus it would be useful if more importance was attached to a data evaluation and processing prior to making a calibration with the hydrological model.

An extension of the model in order to differentiate, if possible, single components on an annual basis does prove necessary in practice in order to be able to describe the hydrological processes in nature. Crucial improvement factors will be a better temperature description and the possible application of transfer of precipitation data over a prolonged period of time or by frequency analysis.

The hydrological ablation model will be improved when a better data basis has been made available. A special description of the temperature differences between ice-covered and ice-free areas is important to the determination of the ablation. A better data basis in basins influenced by runoff from the ice cap is expected to be available within the next couple of years.

In order to be able to apply extreme value analyses in connection with synthetic time series it is necessary to improve the model basis considerably. This will particularly apply to precipitation areas below appr. 100 km^2. In order to remedy this a hydrological model should be enabled to make a better description of runoffs in extreme situations. In respect of conditions in Greenland, this will particularly be in föhn situations with frozen surfaces. I.e. a description going by the worst imaginable case. In a model context, this may be described using for instance föhn criteria (fast dropping absolute air pressure, heavily rising temperature, declining air humidity, and great wind velocity).

Most of the evaporation in Greenland drainage basins also occurs in these situations so it should definitely be possible to describe these conditions in relation to models.

Conclusion

Today, the application of a hydrological runoff model may be used with great precision over drainage basin where the runoff derives from snow melting and rain alone. The NAM model used in this case has, following preceding extensive data analysis work, enabled more certain model calibration producing a reasonable result despite a very brief period of calibration.

Hydrological runoff models describing ablation runoff are possible if the model allows for the parameters controlling the Ice cap melting, i.e. those of heating/cooling, refreezing, snow mobility in the lower part of the drainage basin at the Ice cap etc.

Acknowledgement

For good discussions and critical comments while preparing the hydrological ablation model, we would like to acknowledge colleagues at the Greenland Geological Survey, Roger Braithwaite and Henrik H. Thomsen. Also we thank them for providing the parameter basis of the Ice cap without which this article could not have been written.

List of Symbols

A	Constant (Q-H relation)
A_L	Lake area
B	Constant (Q-H relation)
C_{IF}	Model parameter for interflow
C_{LG}	Model parameter for lower limit for ground water flow
C_{L1}	Model parameter for lower limit for interflow
C_{L2}	Model parameter for lower limit for overflow
C_{0F}	Model parameter for overlandflow
DG	Ground water flow
DL	Flow addition from surface storage
Ea	Actual evaporation
Ep	Potential evaporation
H	Pressure head
I	Snow precipitation
$\triangle H$	Increased pressure head
H_O	Threshold pressure head for lake
IF	Interflow
K_{BF}	Time routing factor for base flow
K_{GF}	Time routing factor for gletscher flow
K_{OI}	Time routing factor for surface and interflow
L	Lower zone storage contents
L^x	Lower zone storage contents (max.)
OF	Surface discharge – overland flow
P	Precipitation
P_{Nuuk}	Precipitation at Nuuk (MI)
Pn	Precipitation surplus
Ps	Melt water
P_{422}	Precipitation at station 422
Q	Discharge
QBF	Ground water discharge
QJF	interflow discharge

QOF Surface discharge – overland flow
r^2 Correlation coefficient
SNE_N Snow magazine in magazine/drainage basin N
T_{HEAT} Heating factor
T Air temperature over the Ice cap
T_{ILUL} Air temperature at Ilulissat (MI)
T_N Air temperature in magazine/drainage basin N
T_{Nuuk} Air temperature at Nuuk (MI)
T_{422} Air temperature at station 422
U Surface storage contents
U^x Surface storage contents (max.)

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Address:
Greenland Technical Organization,
The Directorate,
20 Hauser Plads,
DK-1127 Copenhagen K,
Denmark.