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RUNOFF FORECASTS FOR HIGHLY GLACIERIZED BASINS

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Runoff forecasts for highly glacierized basins

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ABSTRACT: River runoff forecasts for glacierized basins meet practical and scientific needs. Short-term forecasts are of practical and economic value for hydroelectric power production. Long-term predictions are valuable for hydrologic engineering.

Detailed mass balance studies and simultaneous runoff measurements help correct the observed water discharge according to glacier behaviour.

Models that give reliable results 1-3 days in advance have been developed for short-term runoff forecasts. Good weather forecasts can extend this period. There are in principle two different methods presently in use or under development: a physical model based on known processes at the glacier surface, and a mathematical-statistical model based on actual observations of runoff and meteorological parameters.

The problem of using past glacier oscillations, glacier surges, and palaeoclimatic data obtained from the Greenland ice sheet is discussed.

RESUME: Les prévisions de ruissellement des rivières et des fleuves pour les bassins couverts de glaciers satisfont les besoins pratiques et scientifiques. Les prévisions à court terme ont une valeur pratique et économique pour la production de l'électricité. Les prévisions à long terme sont très utiles pour les techniciens de l'hydrologie.

Des études détaillées des bilans massifs et des mesures simultanées de ruissellement aident à corriger les débits d'eau observés selon le comportement du glacier.

On a développé des modèles qui permettent de faire des prévisions sérieuses de 1 à 3 jours d'avance pour les prévisions de ruissellement à court terme. Les prévisions peuvent être plus longues si le temps est beau. Il existe, en principe, deux méthodes qui sont actuellement soit en usage, soit en voie de développement: un modèle physique basé sur les processus connus et ayant lieu à la surface des glaciers et un modèle statistique basé sur des valeurs mesurées des paramètres météorologiques et de ruissellement.

On discute du problème de l'utilisation des données paléoclimatiques et des oscillations des glaciers tirées de la nappe de glace du Groenland.

1. INTRODUCTION

There is great scientific and practical interest in runoff forecasts. For example, for irrigation or water-power planning and for daily management, the cost/benefit ratio will be improved by a good runoff forecast. Even in cases of drinking water supplies, a good long-term forecast may initiate water conservation action in time to avoid later shortage.

For short-term discharge forecasts (covering two or three days in advance) there are two basic methods that have been mainly used for glacier-fed streams. One method is a theoretical model based on known relations between energy exchange at the glacier surface and resulting meltwater production. The other method deals with a model developed from actual daily observations of discharge and simultaneous weather conditions; multiple regression analysis of these data can produce a useful formula for expected daily runoff.

Long-term forecasts are desirable for water-power planning and irrigation construction, because glaciers definitely change the annual discharge considerably if they are growing or receding. However, such forecasts are difficult or almost impossible because glacier behaviour is closely related to fluctuations in climate, which in turn may be extremely difficult to predict. There seems to be a possibility for long-term forecasts only in special cases, such as areas of surging glaciers. Some glaciers seem to surge at fairly constant time intervals, and studies of past surges may, therefore, reveal data to predict future surges. A surging glacier will produce much more meltwater after the surge than before, so if a major surge can be predicted, this means that one can expect a considerably higher annual discharge for several years after the surge. Whether a surge can be predicted to take place within one or two years is, however, still an open question.

2. GLACIER INFLUENCE ON RIVER HYDROLOGY

The hydrology of glacier-fed rivers is strongly influenced by the glacier behaviour, and this influence can be divided as follows:

(a) Glacier release meltwater during a fairly short summer season and the peak period occurs later than most snowmelt peaks. In Scandinavia, for example, glaciers release almost 85 per cent of their total annual discharge during the three months, July, August, and September. This emphasizes the need for large storage capacity in cases where the water is utilized for water-power production.

(b) During a single year the glaciers may increase or decrease in volume. When a glacier decreases (i.e., when it has a negative mass balance) the basin will yield more water than a similar basin without glaciers. On the other hand, a growing glacier withholds some water from the normal runoff in the streams.

The "extra" water or the water withheld by glaciers may cause a deviation from the normal annual discharge (see Tables 1a and 1b). During certain years a glacier may affect the water yield from a basin by as much as ± 20 and 30 per cent.

To predict what will happen during one single summer is almost impossible, at least with the present lack of long-term meteorological forecasts, but attempts have been made to predict water discharge from glacierized basins for short-term periods.

3. METHODS OF MEASUREMENT

Several methods have been used in the past to determine the extent of glacier influence on river hydrology. The total water discharge from a glacierized basin can be measured relatively easily by a standard river gauging station. However, this amount of water may

Table 1a

Example of decreased runoff due to positive glacier mass balance (Nigardsbreen Glacier, W. Norway)

Year	Observed runoff ($10^6 m^3$)	Glacier mass balance ($10^6 m^3$)	Theoretical runoff ("corrected" to eliminate glacier influence)
1964	166.9	+40.2	207.1
1965	154.2	+37.1	191.3
Mean 1964-65	160.6	+38.7	199.3

Water discharge measurements made at a gauging station in Jostedalen, Norway, are greatly influenced by glacier mass balance. In the years 1964 and 1965 the glacier withdrew approximately 25 per cent of total annual discharge from the river. If the glacier had not subtracted any water (ie, it has been in a steady state condition) the basin would have yielded the "corrected" amount of water shown in the right-hand column.

Basin area = 64 km^2, glacier covered part = 47 km^2 (73 per cent).

Table 1b

Example of increased runoff due to negative glacier mass balance (glacier retreat) (Nigardsbreen Glacier, W. Norway)

Year	Observed runoff ($10^6 m^3$)	Glacier mass balance ($10^6 m^3$)	Theoretical runoff ("corrected" to eliminate glacier influence)
1969	249.3	-61.7	187.6
1970	210.9	-21.1	189.8
Mean 1969-70	230.1	-41.4	188.7

The glacier's retreat during the two years 1969 and 1970 gave "extra" quantities of water in the stream, so the observed runoff was far higher than it should have been without glacier influence, which accounted for 18 per cent of the observed runoff. If the glacier had been in a steady state condition, the area would have yielded the smaller ("corrected") amount of water shown in the right-hand column.

For planning purposes (irrigation, water-power) one cannot expect a glacier to retreat indefinitely, that would be too "optimistic"; the reduced figures give a more realistic base for long-term planning.

originate from two different sources: the normal annual precipitation, in liquid or solid form, or the glacier contribution in the years of negative mass balance, when an extra amount of water is added to the precipitation. During recent decades most glaciers in the world have been in an almost continuous state of retreat and rivers have yielded more water than before this period of retreat started, assuming the precipitation has remained the same.

To determine this extra water contribution from glaciers it is necessary to measure the glacier behaviour for each single year. A detailed study of the glacier mass balance will, if it is carried out properly, provide fairly reliable figures, normally expressed as a water volume for each single glacier, valid for one glaciological year. A glaciological year is roughly the same as a hydrological year, beginning in the fall when winter snow cover starts to accumulate and ending at the end of the next summer's melt season.

A complete mass balance study includes both a full and detailed survey of winter accumulation (winter balance) and measurements of the total summer melt (summer balance). The difference equals the net mass balance, which may be positive or negative. Details of the measuring techniques are not dealt with here because they are well documented in the literature [1].

It is possible to assess the glacier mass balance, however, by studying the situation on the glacier at the end of each summer only. A detailed survey of the remaining snow in the firn area and knowledge of the summer's total icemelt in the ablation area form a base for calculating the net mass balance for that year. Such studies have been made in the Alps, for example, over a long series of years, and the technique is now fairly well developed. However, for scientific reasons it is desirable to make a complete mass balance study. Then it is possible to investigate the relative influence of the two main factors that are responsible for the glacier mass balance: winter accumulation and summer ablation. When only a single survey is made at the end of the melt season, the net mass balance is obtained, but it is almost impossible to explain whether, for example, a positive balance was due to a heavy winter snow cover or a cool summer.

The net mass balance can also be obtained from ice discharge measurements in a cross-section of the glacier at the equilibrium line. This method is based on the fact that an excess amount of snow in the upper part of the glacier turns into firn at the end of the melt season and adds to the glacier mass. Similarly a certain amount of glacier ice melts away on the tongue and is replaced by ice flowing through the cross-section. If the glacier is in balance, the amount of remaining snow (turning into firn) at the end of the summer equals the amount of glacier ice that has disappeared on the tongue. The same amount of ice will discharge through the cross-section.

If the glacier mass balance is positive, a larger amount of firn has been produced and, theoretically, a larger amount of ice must discharge through the cross-section. This will, in turn, feed more ice into the ablation area. However, a certain part of it will not melt and, consequently, the tongue will eventually start to advance.

Observations of ice discharge through the equilibrium line cross-section will, therefore, on a long-term basis provide data on the glacier behaviour. Even for a single year, comparisons could be made between ice discharge and the amount of ablated ice below the equilibrium line, giving a direct measure of that year's mass balance. For example, if the amount of ablated ice is less than the ice discharge, the glacier has a positive balance year. A definite condition for successful use of this method is a good knowledge of the glacier's cross-sectional area at the equilibrium line.

In general, with the use of better logistic aids and the application of more sophisticated surveying equipment, mass balance results have become fairly reliable, but the work is still very time-consuming, laborious, and, therefore, costly. Mass balance studies can, therefore, be carried out only on selected glaciers or within basins where a great financial interest is involved in the utilization of the river water.

4. CALCULATIONS OF NORMAL STREAMFLOW

For planning purposes it is necessary to use long-term normals of water discharge, preferably from different parts of large basins. There are almost no problems in obtaining such normals for glacier-free basins; a twenty or thirty year record of annual discharge is a good base for planning purposes. However, if glaciers are present in a basin, the long-term average cannot be used directly, because of the impact of glaciers on river hydrology. For example, if the glaciers have been in a continuous state of retreat, all previous data are generally too large because they include an "extra" amount of water due to glacier shrinkage. One cannot expect glaciers to retreat and yield extra water to the streams indefinitely, so for long-term planning pusposes it is necessary to subtract this amount of water from the observed values.

If data are available on glacier mass balance for all years of stream gauging, each year's annual discharge can easily be corrected accordingly. If such annual mass balance data are not available, certain estimates must be made. Previous glacier photographs or local surveys may provide data to estimate the previous ice volume, and by comparison with today's situation, the difference in volume could be calculated. By distributing the corresponding water equivalent over the intervening years, an average annual correction can be made.

In many cases, however, no long-term observations are available and no previous glacier observations have been made. The normal procedure is then to start river discharge measurements and simultaneous mass balance studies for at least one or two glaciers in the basin. Annual corrections in runoff figures can then be made (positive or negative according to glacier behaviour) and a "corrected" discharge figure obtained for each single year. Such figures would express the amount of water that one could expect if the glaciers were in a steady state condition; ie, a way to "remove" the glacier effect from the basin (compare Tables 1a and 1b). (Note: if glaciers were physically removed from the basin, one might probably expect a change in annual precipitation due to changes in the local climate and, hence, of the condensation effect on cold surfaces.)

5. SHORT-TERM FORECASTS

In basins with many glaciers and limited possibility for water storage—a combination which is fairly common—it is of great economic interest to obtain short-term runoff forecasts. These can, for example, improve the efficiency of the daily water management in a power station, because if a change in runoff conditions can be predicted one, two, or three days in advance, power production and subsequent transmission to or from other points in the grid system can be planned accordingly. Therefore, efforts are made to develop methods for such forecasts.

So far, two different methods have been tried to obtain a formula for short-term runoff prediction for glacierized basins; the "theoretical" model for glacier melt using known glaciometeorological relations, and the "statistical" method based upon correlation of discharge and meteorological parameters.

(a) The Theoretical Model

Both in the U.S.A. [2] and in Canada [3] attempts have been made to develop models to calculate the daily runoff from glacierized basins. The input consists of selected meteorological parameters, basin characteristics, etc., and the construction of the model is based upon known formulas within glacier meteorology.

The American study was related to water production and flow within a single glacier, whereas the Canadian study was concentrated on glacierized basins in the catchment of the North Saskatchewan River, which drains from the eastern Foothills of the Rocky Mountains across the Prairies to Hudson Bay. There is an increased irrigation demand on the Prairies, so a good knowledge of water resources is obviously desirable.

Attempts were made to relate the daily runoff to incoming radiation, air temperature, atmospheric moisture, wind velocity, and precipitation. The influence of glacier melt and precipitation on the daily runoff was calculated for separate 100-m elevation bands, and a runoff component was also included for the non-glacierized part of the basin.

The model was based upon the energy balance equation:

$$H = S(1-a) + R + H_s + H_l + H_r$$

where: H = total energy transfer to (or from) the glacier surface;

S = incoming shortwave radiation, in certain areas reduced for slope and orientation;

a = albedo;

R = longwave radiation (mainly outgoing);

H_s = sensible heat transfer by convection;

H_l = latent heat transfer by evaporation or condensation;

H_r = heat advected by rain.

Each of the components were calculated according to known relationships; for example, incoming radiation was calculated for various areas according to slope and orientation and known sun angles throughout the day. Efforts were made to calculate direct (clear sky) and diffuse (cloud cover) radiation separately, based upon recorded hours of sunshine. Corrections were made for energy absorbed by water and ozone.

Albedo for ice was kept constant at 0.40 whereas the albedo of snow cover was allowed to undergo a continuous decrease from an original value of 0.80. The border between exposed ice and snow cover on the glacier was assumed to rise up to a given altitude during the summer.

Longwave radiation was calculated from a formula [4] that takes into account the amount of cloud cover, calculated from the recorded hours of sunshine.

The turbulent transfers of sensible and latent heat were also calculated from formulas, but they were modified slightly to obtain a fairly simple approximation.

In addition to these calculations of the various components in the energy balance equation to obtain the amount of melt in various parts of the basin, some additional computations must be made. For example, the liquid contribution to streamflow from rainfall must be modified if the air temperature is close to 0°C, because parts of the precipitation may fall as snow in the higher sections of the basin. Further, a gradual increase in precipitation with height was assumed to take place up to 2600 m, thereafter it was assumed constant. Similarly, other meteorological parameters were calculated for each single 100-m elevation band, based upon observations at the meteorological station.

The final model was tried on two glaciers situated in completely different environments: Peyto Glacier in the Rocky Mountains (continental) and Berendon Glacier in the Coast Mountains (maritime). Four meteorological parameters were used (air temperature, atmospheric moisture, wind velocity and precipitation).

For Peyto Glacier, the daily computed values proved to be within ± 21 per cent of the observed values, whereas they were closer to the observed ones for Berendon Glacier. For most of the melt season the daily basin runoff can be calculated with an average accuracy of 10-20 per cent provided basic meteorological observations are available for one station within or close to the basin (see Fig. 3).

(b) The Statistical Model

A visual inspection of a diagram showing daily variations in meteorological parameters and daily discharge from a glacierized basin, may reveal certain correlations. A warm period will, in general, cause a rise in water discharge, as will also a rainy period. In Maritime catchments a period of humid and mild winds will promote melting and also cause a rise in runoff [5, 6].

The correlation between variations in one of the meteorological parameters and the discharge can hardly be determined directly from a diagram of this type. The impact of various parameters cannot be easily observed because almost all of them show variations at the same time. It would be possible to approach the problem in a strictly theoretical manner, using various formulas that have been developed for energy exchange between the atmosphere and a glacier surface—similar to the approach in section (a) above.

Due to a desire among engineers at the Norwegian Water Resources and Electricity Board to develop a method for runoff forecasts in glacierized basins, a special study of this problem was started in 1967 [7, 8, 9]. A step-wise multiple regression analysis was performed, in which the daily discharge values were regarded as the dependent variable, and various meteorological parameters as independent variables. A similar study was later made by Lang [10] for Alpine rivers. It should be noted that no physical or heat-exchange formulas were used in this study--it is a purely statistical method.

It is assumed that there exists a linear correlation between the daily water discharge and the independent meteorological parameters calculated as daily mean values. The regression analysis makes it possible to obtain a formula of the following general form:

$$Q = k_1X_1 + k_2X_2 + \ldots k_nX_n + k$$

where: Q is the daily discharge,

$k, k_1, k_2 \ldots$ are constants,

$X_1, X_2, X_3 \ldots$ are independent variables, ie, the meteorological data used in the analysis

The normal procedure is to find the value of the coefficients k_1, k_2, etc., and their levels of significance.

In many cases it proved unnecessary to include all the independent variables to obtain a formula that could adequately describe the daily discharge. It was found that the discharge could be well explained with the use of only two or three meteorological parameters. When more variables were included the residuals did not decrease significantly. Therefore, the analysis was concentrated on developing a model based upon one, two, or three variables. The computations were done on a CDC 3200 computer, by means of a standard program for step-wise multiple regression analysis [11]. For the years 1967, 1968, and 1969, various formulae were developed for each of the five glaciers that were selected for this study. The resulting multiple correlation coefficients for the resulting formulae ranged between 0.70 and 0.94.

The meltwater discharge from a glacier is normally time-delayed in relation to the factors that cause the melt. For example, on a long valley glacier it is possible that one day's melt in the firn basin would not reach the tongue and discharge from the glacier until one or more days later. Consequently, it will often be possible to predict water discharge for the following few days if melt conditions (i.e., meteorological conditions) are known for one given day. The formulas that were developed in Norway showed that for many glaciers it was possible to express the next day's runoff with a fairly high degree of reliability (difference between calculated and observed runoff was well within 20 per cent, and for some glaciers less).

The meteorological data used in the study were obtained from various observation points on the glacier, near the glacier, or down at a permanent meteorological station in a neighbouring valley. Direct weather observations on the glacier proved to be the best for use in the model. However, the running costs for a station on the glacier are so high that attempts were made to use data from standard meteorological stations, although they are often located in a completely different environment, far lower down in inhabited valleys. Data from radiosonde records taken at the 850 millibar surface were often better because the meteorological conditions at this altitude are more similar to those at the glacier.

The following parameters were included in the analysis: air temperature, precipitation, atmospheric moisture, wind velocity, cloudiness, and incoming radiation (only for stations equipped for such observations). Daily mean values were calculated for all these variables and punched on standard computer cards. Daily sums of water discharge, observed at a gauging station close to the glacier front, were also transferred to punch cards. Data from several years for each single glacier basin were handled separately and different formulae were obtained for each basin. As a first attempt, however, to investigate which of the various meteorological parameters was best correlated with the daily discharge, special diagrams were plotted. In each case one meteorological variable was plotted against the discharge and the correlation coefficient calculated.

Two examples are shown in Figure 1a-b where daily mean air temperatures are plotted versus runoff. For a glacier situated in a continental environment (Memurubreen Glacier) a fairly good correlation was found (Fig. 1a) whereas no correlation was found for a glacier in the maritime climate (Aalfotbreen Glacier), an apparently surprising result. Ablation variations on this glacier seem to be more closely connected to atmospheric moisture; an almost constant condensation takes place on its surface due to the moist Atlantic air masses moving over the glacier.

The correlation coefficients for the various meteorological parameters are shown in Figure 2a-b for the same two glaciers. From these diagrams it can be seen that there is a time lag between weather and runoff. This makes it possible to construct a model for discharge forecasts, so that, in the following analysis, all meteorological variables for the last three days were included. Various models were then obtained for each single glacier. The analysis was later extended to two or three day running means which gave slightly different formulas, but a higher multiple correlation coefficient was generally obtained.

Three of the independent variables were almost always selected by the computer to be included in the resulting formulas: temperature (t), precipitation (P), and wind velocity (V). However, after a long series of experiments to combine various variables (sums, products, exponential forms, such as t^n, etc.) it became clear that the best result was obtained when certain products of variables were used instead of single variables. For example, one variable could be the product of temperature and precipitation, another variable would be the product of temperature and windspeed, and, in most cases, the temperature itself would be the third variable. The general form of the resulting formula was:

$$Q = k + k_1 \cdot (tV) + k_2 \cdot (tP) + k_3 \cdot (t)$$

This formula will, for most glaciers, express the discharge (Q) for the next day. However, if each of the meteorological parameters are calculated as running means for two or three days (depending upon the size of the glacier) the formula makes it possible to predict water discharge approximately two days in advance.

A check of the formula was made by applying it to a previous year's observations. Discrepancies between calculated and observed discharges were in general less than 5 per cent. For single events, however, the difference could be as large as 15 per cent (see Fig. 4).

It is difficult to explain the physical processes that are connected to the various parts of the resulting formula. Many of the "independent" variables are in fact intercorrelated. Correlation analyses made on the daily values have shown, for example, that air temperature and humidity have a correlation coefficient of 0.6-0.8.

The term (tV) might represent the turbulent transport of sensible heat to the glacier, but due to the correlation between temperature and humidity it is supposed that it also represents a considerable part of the turbulent transport of latent heat. Further, air temperature is most correlated to incoming radiation.

For some of the glaciers it could be shown that the term (t) could be substituted with (10-C) where C is cloudiness expressed in tenths. This term is again related to incoming radiation. However, it was impractical to use cloudiness as one of the variables because it is a variable that is difficult to include in a weather forecast. It is, therefore, not suited for future development when, hopefully, data from weather forecasts will be used as variables for the calculations, thus increasing the length of time for which the precipitations are valid.

6. LONG-TERM FORECASTS

Glaciers are sensitive to variations in climate, a deterioration normally causing an advance. They have therefore been used as a tool in investigations of past climatic changes. Such relatively slow glacier variations will, of course, have a certain influence on the annual runoff (compare for example [12]). Some glaciers, however, make sudden, rapid advances that are apparently not related to variations in climate, but they are hydrologically important.

In recent years it has been shown that some glaciers tend to surge at fairly regular intervals [13]. If the period, which may be several decades or even centuries, could be determined, it would be possible to predict a considerably higher water discharge during a period of many years after a surge because so much more ice is then moved to lower altitudes, and the rate of melt is greatly increased.

However, the number (and total area) of surging glaciers is probably small compared to the total number (and area) of glaciers in basins that are considered for water-power development or irrigation constructions. Further, it is still an open question whether surges can be predicted with a reasonable reliability.

A better tool for long-term forecasts may be based upon results obtained by deep drilling in the Greenland ice-cap. A 1400 m vertical ice core was recovered from Camp Century on the North Greenland ice-cap, and analyses were made on the content of the stable isotope ^{18}O relative to ^{16}O in the ice. The concentration of the heavy isotope ^{18}O in high polar snow is higher if the temperature was relatively high when the snow formed. This causes seasonal variations in the composition of accumulated snow and ice so long-term climatic variations are similarly depicted in the variation (with depth) in the $^{18}O/^{16}O$ ratio.

A detailed study of the upper part of the ice-cap, representing the last 800 years, revealed periodic variations in the oxygen-18 content. Periods of approximately 63 years between climatic optima could be estimated [14]. This is in good agreement with 66-year periods of climatic fluctuations found by studies of the Greenland fauna [15].

A Fourier analysis revealed superimposed "waves" of 78 and 181-year periods, and such periods have previously been related to sun activity. For example, there exists a 78-year period in variations in length of the well-known 11-year sunspot cycle [16]—they change between approximately 10 and 12 years.

If a graph is made of these two harmonics against a linear time scale, one can "extrapolate" this curve into the immediate future. This was done by W. Dansgaard (compare [14]);the result is shown in Figure 5. Although such a long-term forecast may be affected by incidental events, it indicates a continuous cooling throughout the coming two or three decades, followed by a gradually warmer period with a climatic optimum about year 2020 A.D.

This expected climatic fluctuation will most certainly be reflected by glacier activity—although many large glaciers and glaciers in Arctic areas may react slowly. For most glaciers in temperate regions, a period of growth must now be expected, and for some glaciers it seems to have started. The Nigardsbreen outlet glacier from the Jostedalen ice cap in Western Norway has shown several years of positive balance since detailed mass balance studies started in 1962. In spite of years of considerable net loss, this glacier has increased its volume by more than 4 m of water equivalent during the period 1962-71, see Figure 6.

7. CONCLUSIONS

Examples of studies made in various countries on the possible use of runoff forecasts in glacierized regions indicate that it is possible to predict daily discharge variations. Depending upon local topography and sizes of glaciers, such forecasts can be made one or several days in advance, particularly if good weather forecasts are available.

Some of the methods seem to need further development to be easily applicable to any given basin as a practical tool in the daily water management, for example, in hydroelectric power production. So further research and experiments with other models should be encouraged.

Although long-range weather forecasts (for several weeks) are still too unreliable to be used in the models for daily runoff prediction (for example, throughout a whole melt season) it already seems possible to include weather forecasts made for 3-5 days in advance. This means that daily runoff from glacierized basins may be predicted almost a week in advance. Reliability will be increased by refinement of the models and improved weather forecasts.

Long-term glacier variations have taken place in the past and will take place in the future. Based upon statistical analysis of climatic fluctuations in the past, as depicted in variations in oxygen-18 content in the Greenland ice-sheet, we must be prepared to face a climatic deterioration in the coming 10-20 years. Glaciers will react to this fluctuation by volumetric growth—ice will again flow into newly exposed valleys, and a most important hydrologic result will be experienced: glacier streams will yield less water than before. Old "long-term" discharge records made in the past 30-40 years will prove unreliable or almost useless for hydrologic engineering in glacier areas unless drastic corrections are made to reduce these too optimistic runoff records. This is an important task for tomorrow's glaciologists.

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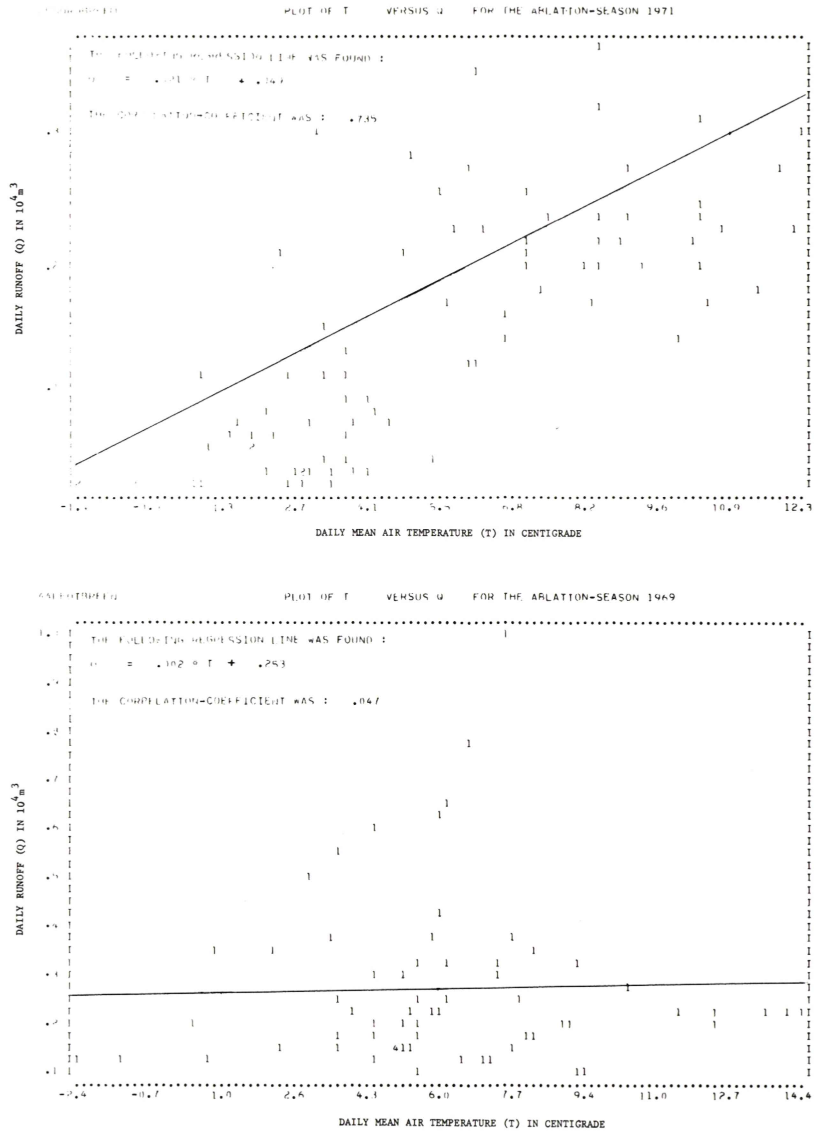

Fig. 1a-b. Linear plots (made by computer) of daily runoff (Y-axis) and daily mean air temperature (X-axis) for two selected glacier basins in Norway.

There is a good correlation (r = 0.74) for a glacier situated in a continental environment, whereas the maritime and extremely temperate Glacier Aalfotbreen does not seem to react significantly to variations in air temperature. It can be shown that other parameters are of greater importance for this glacier (see Fig. 2a-b)

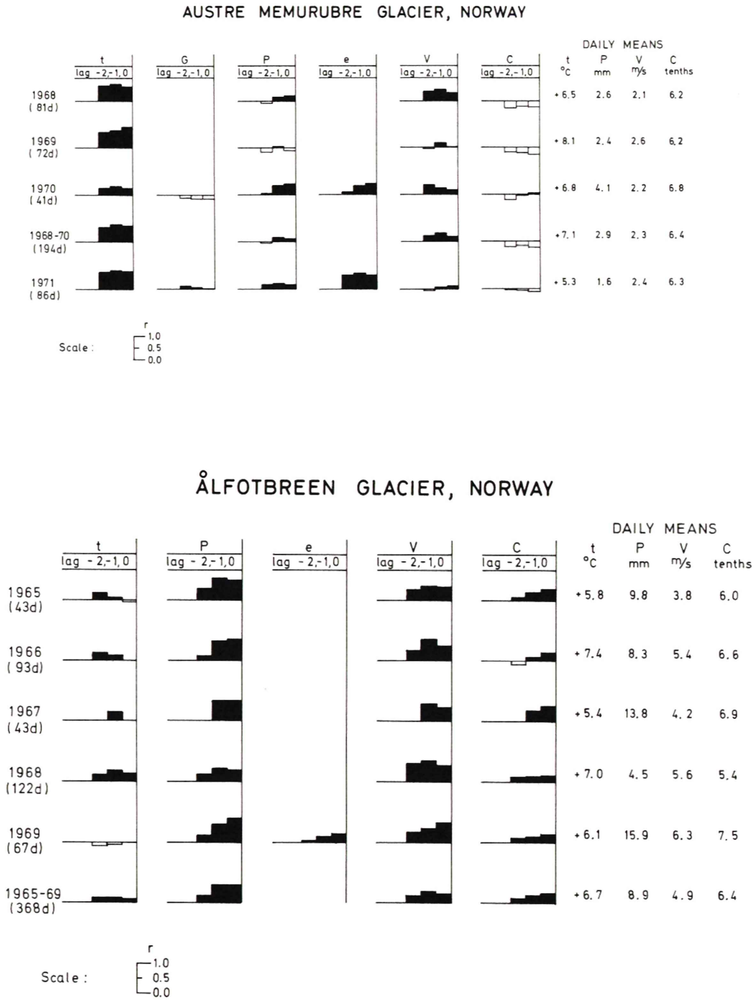

Fig. 2a-b. Daily runoff was correlated with various meteorological parameters for the same day, one day before, and two days before. The correlation coefficients were calculated in all cases, and they are shown in this diagram, where: t - daily mean air temperature, G - global radiation, P - precipitation, e - water vapour pressure, V - wind velocity, C - cloudiness in 1/10.

Note that temperature is less correlated for the "maritime" glacier Aalfotbreen, where, for example, wind velocity is far better correlated

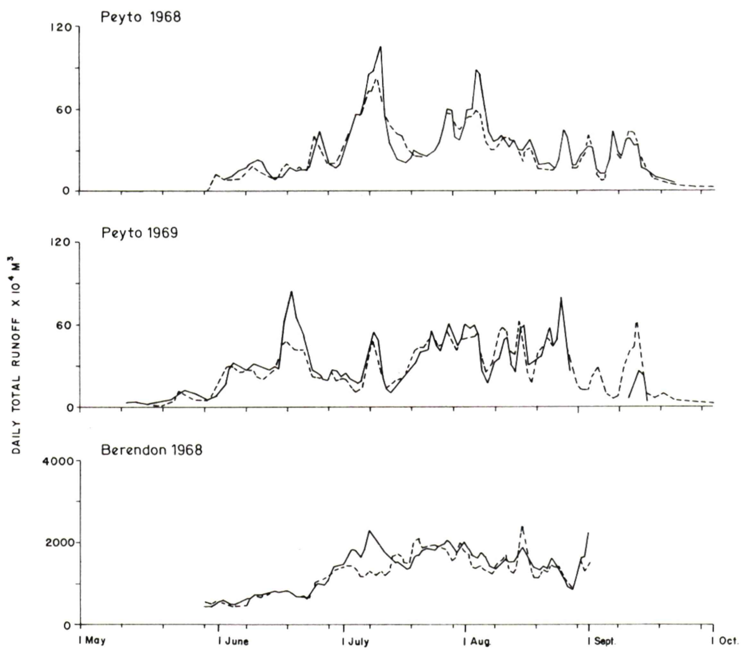

Fig. 3. Observed and calculated discharge from Peyto Glacier, Rocky Mountains, Canada, for 1968 and 1969 and for Berendon Glacier, British Columbia, Canada, for 1968. All calculations were made from the model developed by Derikx and Loijens (1971) [3]. Solid line = observed values. Dashed line = calculated values. Runoff in $10^4 m^3$. Horizontal scale divisions are 10-day periods

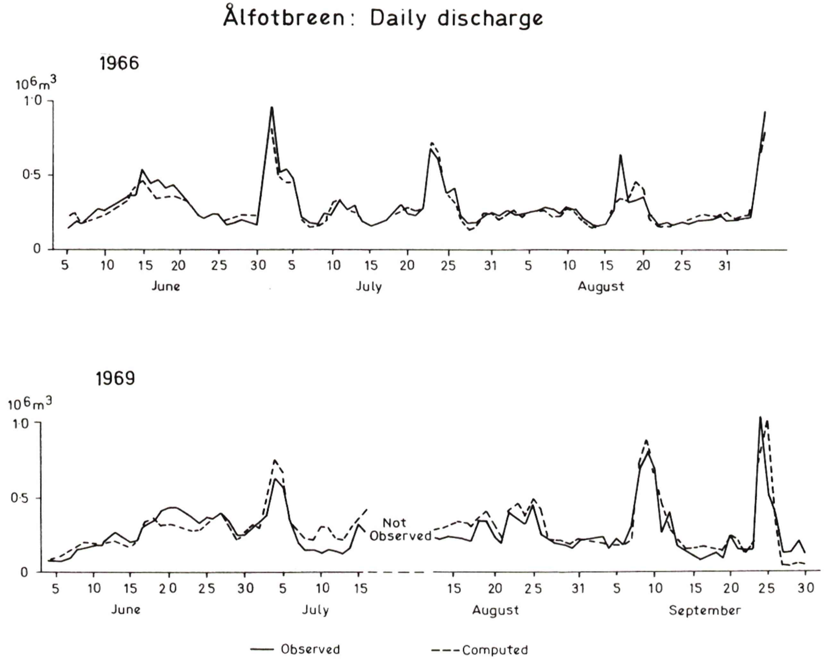

Fig. 4. Observed and calculated runoff from the Aalfotbreen Glacier in Western Norway. Daily runoff was calculated from the equation:

$$Q = 3.54 + 0.16(tP) + 1.43(t) + 0.11(tV)$$

that was developed by a stepwise regression analysis of 10 observed variables (different meteorological data from several stations) and combinations of these for 392 days of observation (Roald, 1971) [17]

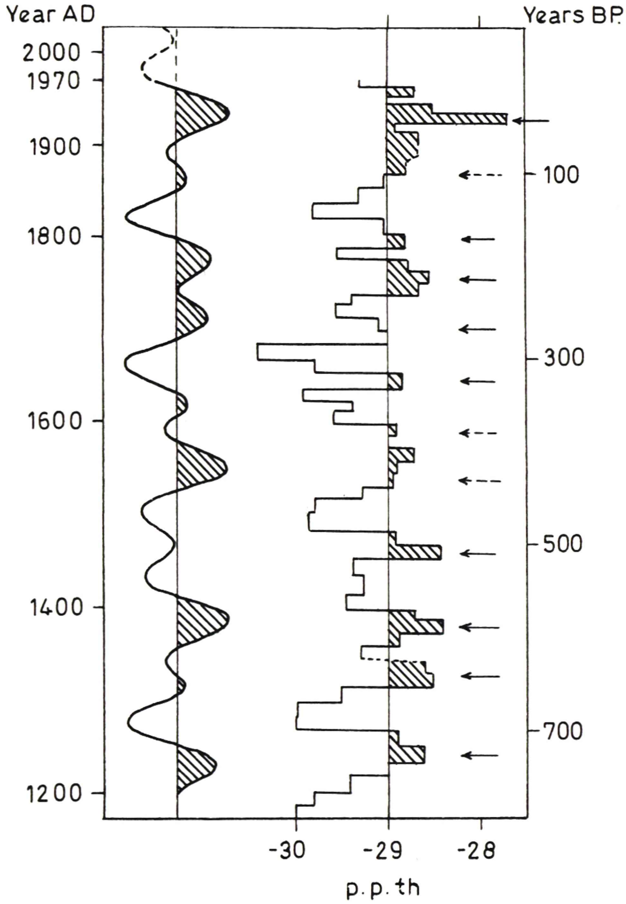

Fig. 5. Right: Variations in the isotopic composition (oxygen-18/ oxygen-16 ratio) in an ice core from Camp Century, Greenland, plotted against a linear time scale showing years since deposition. Hatched areas indicate relatively warm periods. Arrows point at climatic optima - indicating a climatic oscillation with a period of approximately 63 years.

Left: Results from a Fourier analysis. Two dominant harmonics are synthesized and projected into the future. This indicates a continuous cooling through the next 1-2 decades followed by a climatic optimum about year 2020. (This illustration was redrawn from Johnsen, Dansgaard, Clausen and Langway, 1970) [14]

Nigardsbreen, Norway — Mass balance

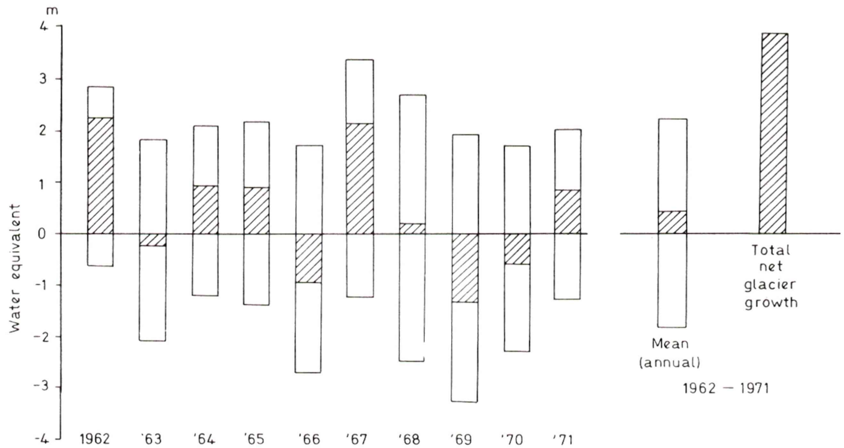

Fig. 6. Diagram showing winter balance (positive bars) and summer balance (negative bars) expressed in water equivalent figures. The difference—net balance—is shown as hatched parts of the bars. In spite of years of strongly negative balance (for example 1966 and 1969) this glacier has shown a growing tendency. During the 10-year period the glacier has added to its volume more than 4 m of water equivalent (evenly distributed on the entire glacier surface); a similar trend is found on other glaciers under observation in Norway. This is in sharp contrast to previous decades, when glaciers generally were retreating

DISCUSSION

H.S. Loijens (Canada) - Dr. Lang showed us yesterday that, in order to obtain the best runoff forecast of a glacierized basin in Switzerland, the melt season had to be divided into three distinct periods for which the statistical parameters were computed. In Canada Derikx and Loijens (1971) used a distributed linear time-variant approach in their runoff simulation model to take into account changes in the glacier runoff system in the course of the ablation season.

Could you explain why this is not apparent in your data from Norway? Do you find any differences in the statistical equations and parameters that might be related to maritime and continental glaciers?

G. Østrem (Norway) - We recognize, of course, that the surface characteristics of glaciers change throughout the melt season and that the melt pattern, therefore, must also change. However, the Norwegian Water Power Authorities wanted to have a simple model which can be easily applied in all seasons and in all areas. They also wanted a model based upon not more than three meteorological parameters: temperature, wind, and precipitation, which are easily obtained everywhere. By using these parameters we have obtained fairly good results. We could certainly improve our model by including radiation data, humidity, etc., but our "customer" is looking for a simple operational model. Further the improvements such additional data would add are limited. For example, examine the section in the paper where ±5% reliability is demonstrated for daily discharge forecasts.

A.D. Stanley (Canada) - I congratulate you on your attempt to find a simple model for glacierized basins. However, you may care to comment further on the formula given under Figure 4. The equation contains the term 3.54, which would indicate that for periods with no rain and little wind, and temperatures at zero, the basin would have a constant outflow.

G. Østrem (Norway) - Theoretically the formula will obviously not work well if $t = 0°C$ and if there is no precipitation. However, these glaciers where the data were obtained were located in an extremely maritime environment where precipitation is very abundant and low temperatures are infrequent during the main melting season. Therefore, the restrictions rarely apply.

M.F. Meier (U.S.A.) - The formula shows that solar radiation is not an important term in determining glacier melt. However, most micro-meteorologists studying the heat exchange over snow and ice surfaces agree that solar radiation is a very important factor. Would you care to comment?

G. Østrem (Norway) - It surprised me and many others that incoming solar radiation was not found to be a significant factor. However, temperature is often strongly related to incoming solar radiation. Thus, the temperature term is a fairly good index for radiation.

In developing the formula we tried to introduce the term (10-C) where C is cloudiness in tenths, but it did not substantially reduce the residuals. Cloudiness over the glacier, furthermore, is complicated to observe, and to include it in the formula would violate one of our objectives to develop a simple formula based upon easily obtainable meteorological data.

We also tested the effect of other terms, such as the product of wind and vapour pressure (which might have provided an index of the turbulent latent heat transfer to the glacier surface) and various powers of the temperature. None of these improved the results significantly and they were therefore omitted.

M. Roche (France) - Le modèle statistique proposé ne contient aucun terme de persistance, ni pour les débits eux-mêmes (effet de stockage), ni pour leurs facteurs conditionnels. Ceci revient à dire que même à l'échelle journalière, le laminage des quantités d'eau produites par la fonte est nulle et qu'il n'y a pas d'emmagasinement de chaleur dans le bassin (notamment dans le glacier).

En ce qui concerne les variations cycliques à courte période, c'est à dire quelques années ou quelques dizaines d'années, elles résultent généralement d'un effet de moyenne mobile sur les phénomènes climatiques ou hydrologiques. Cet effet de moyenne mobile peut être engendré naturellement par l'effet de stockage dont sont capables les lacs et les glaciers. Il dépend des masses et valeurs Groënland mis en oeuvre dans chaque cas particulier et les résultats obtenus au Groënland ne sont peut-être pas transposables.

G. Østrem (Norway) - In this model we do not consider storage. We are searching for a method by which glacier runoff can easily be forecasted from readily available meteorological parameters. The model is purely statistical and, to put it bluntly, we do not care about the physics of the situation as long as we can, with reasonable accuracy, forecast the amount of meltwater a day or two in advance.

The results from the Greenland ice core were only introduced to demonstrate how Dansgaard and his collaborators think the climate may have changed in the past and how it may change in the future. The idea that a probable long-term climatic deterioration has now started can be supported from mass balance data obtained from Nigardsbreen, Norway. Data have increased during the last 10 years, and I want to emphasize that we have to consider possible future climatic changes when plans are made for hydroelectric development of highly glacierized basins.

F. Müller (Switzerland) - I am concerned about the discussion so far regarding the influence of the radiation parameter in runoff forecast models. Dr. H. Lang showed that the correlation between discharge and radiation for a glacierized area in Switzerland is very low. This morning Dr. P. Jolly presented a case where both the correlation to temperature and to radiation was extremely high. Now, Dr. Østrem, in his reply to the comment from Dr. M. Meier, indicates that the inclusion in the model of the radiation parameters is impractical and is not suited for future development. Everyone, who has worked in glacial micro-climatology, knows that radiation is extremely important in the energy balance of snow and ice melting. Only during days of rain and heavy overcast will the turbulent energy exchange dominate. Data for those days should be treated by a separate equation. Any runoff forecast model claiming general application must include radiation. The fact that it is difficult to obtain good radiation data cannot be used as an excuse for ommitting this parameter.

G. Østrem (Norway) - I am fully aware of the significance of radiation in a physical model, but as I said before we are not concerned about the physical aspects. We were concerned with purely statistical relationships, and I can only assume that the temperature term is an adequate index of the radiation term. However, if radiation data were available for the catchment we would, of course, be happy to include such data in our model.

H. Lang (Switzerland) - Through the discussion of this paper, it is evident that some people were surprised that there can be a negative correlation between glacier discharge and global radiation. This phenomenon is very familiar to me and in the paper I presented, similar negative correlations were shown but I did not pay special attention to this fact as these effects were already treated in detail in a previous paper presented at the IASH-General Assembly Commission on Snow and Ice, Berne, 1967. This stochastic pattern rises in such a statistical treatment when a basin is involved where the liquid precipitation has a dominant influence to glacier runoff. This means that precipitation, connected mostly with low incoming shortwave radiation, causes fairly high runoff, which is often intensified by high melt-rates from latent heat. On the other hand, the discharge is comparatively low on days with high global radiation; in some cases it is lowered by evaporation (loss of energy) and also by low incoming longwave radiation (no clouds or only a few).

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