

A STUDY OF SEDIMENT TRANSPORT

IN

NORWEGIAN GLACIAL RIVERS

1969

A study of sediment transport in Norwegian glacial rivers  
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Permission to translate this Norwegian report was kindly given by G. Østrem, and the translation by Helga Carstens, while she was in Alaska, is greatly appreciated. Unfortunately, Mrs. Carstens returned to her homeland, Norway, before final editing of the manuscript could be completed. Consequently, any errors in translation are due to the editor, and for these errors, the editor apologizes to the authors. Not included in this translation is an English summary contained in the original report. To keep printing costs down, the original figures and tables, which fortunately had English titles, are used in this translation.

This report is the first of a series of reports being prepared for the Norwegian Water Resources and Electricity Board. The second report for 1970 has been published with an English summary and contains an extension of the data contained in the 1969 report. Because this work deals with problems very similar to those in Alaska, it was decided to translate the first report and circulate a limited number of copies to workers in the U. S. and Canada. Research very similar to the Norwegian work was initiated in Alaska under the editor's direction in cooperation with the U. S. Geological Survey. This work and the translation of this report were supported by funds provided by the United States Department of the Interior, Office of Water Resources Research (Proj. A-042-ALAS), as authorized under the amended Water Resources Act of 1964.

G. L. Guymon

THE NORWEGIAN WATER RESOURCES AND ELECTRICITY BOARD

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Report No. 6/70

INSTITUTE OF WATER RESOURCES

DEPARTMENT OF HYDROLOGY

OSLO

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## PREFACE

Large quantities of sediment are produced by glacial erosion. Some of the material consists of large rocks which are transported by ice and deposited at the edge of the glacier. This material provides the base for the moraines in front of glaciers. Some of the large rocks are transported in the bottom layer of the glacier which then acts like a gigantic "sand paper" against the rock bottom. This "sand paper" action provides a fine material which is later transported by melt water flowing underneath the ice. It is this material which gives glacial rivers their grey color. Since the glacial rivers may be harnessed for future power stations, it will be necessary to study the sediment transport in these rivers.

Methodical studies of sediment transport in selected rivers have been done by Brekontoret [the Glacier Studies Section of the Institute's Department of Hydrology; ed.] since 1966. This report contains the results of sediment studies made in 1969. In addition, data from earlier studies are included for comparison. These studies are the result of cooperation between the Institute of Water Resources and Stockholm University. (The Institute of Natural Geography at Stockholm University has funded some of the work as a part of scientific research into the eroding force of glaciers and their landscaping effect.) A Swedish research engineer and a Swedish student have therefore worked part of the summer at the Nigardsvatn Glacier, where the sedimentation process specifically was studied. Moreover, one full position at the main office of the Norwegian Water Resources and Electricity Board is supported by Swedish funds. Most of the work on the measurements has been done here, except for the observations, from the Nigardsvatn and Vesledalsvatn Glaciers, which have been processed in Stockholm.

This cooperation has been useful for both parties. On one hand, the Norwegian Water Resources and Electricity Board has gained important data on problems that will be encountered when the glacial rivers are exploited for energy production. On the other hand, Stockholm University has made possible an analysis of the observations in such a way that results of pure scientific interest have been obtained. As far as we know, such detailed studies have never before been made of the sedimentation processes at so many different types of glaciers.

The intention is to continue these studies over several years in order, among other things, to even out the variations in sediment transport that will occur from one year to the next. We know that these variations can be quite large, and a clear picture of sediment production at the chosen number of glaciers cannot be obtained unless observations from several years of study have been collected.

Knowledge of sedimentation process in natural lakes with an inflow from glacier rivers can provide a base for design of artificial settling basins. Such basins may be necessary at diversion intakes in rivers with a high sediment load, and we believe it therefore to be of great importance to study sedimentation in lakes of various sizes. Parts of

this report concern this problem.

The results of sedimentation studies have previously been published in Brekontoret's yearly reports on glaciological studies in Norway (see Østrem and Pytte, 1968; Pytte, 1969). Editorial reasons have made it practical to extract the sediment studies and publish the results in the form of a special report. This report is the first in a series of yearly publications concerning the results from sediment studies.

Most of the primary data for this report were gathered by a group of students assisting in the field work in the rivers and lakes in the summer of 1969. The laboratory analysis of sediment tests was done partly in Stockholm and partly in Oslo, where the Norwegian Polar Institute provided the facilities. Bard Braskerud made the final illustrations and Mrs. A. Hertzberg typed the final manuscript and prepared the text for offset reproduction.

Gunnar Østrem

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## THE OBJECT OF SEDIMENT STUDIES OF GLACIAL RIVERS

The studies of transport of solid particles in our glacial rivers may be said to have a double purpose. First of all, such studies are in a direct way useful for those who wish to exploit the water, either for drinking purposes or for the production of electric power. Secondly, the studies have a scientific value, as the glaciers over a longer period have a great landscaping effect. Geographers and geomorphologists have always wished to obtain knowledge of the eroding velocity of glaciers. In this respect, studies of sediment transport in glacial rivers may furnish valuable information.

The present studies were begun for both practical and scientific purposes. This came about through a cooperative effort between the Institute of Water Resources and the Institute of Natural Geography at Stockholm University. The latter institute has in previous years performed some studies of glacial erosion in Northern Sweden (e.g., C ve and Norrbin, 1965). When plans for exploitation of Norwegian glacial rivers were made, the practical purposes of sediment studies of Norwegian rivers could easily be combined with the need for scientific data from different climatic regions. Considerable contributions towards these studies have therefore been made from Sweden, mainly in the form of manpower. The field work has mainly been funded by the Institute of Water Resources. Contributions have also come from NTNF (The Royal Norwegian Council for Technical and Industrial Research; ed.), which especially contributed to studies at Nigardsbreen Glacier. The collected data have been analyzed with regard to daily sediment transport at all gauging stations and sedimentation in water or specific parts of the rivers. The results have been compiled in this report.

The map on page 6 shows the location of the gauging stations. The observation stations were chosen in order to obtain data from different types of glaciers, from arms of large plateau glaciers, and from glaciers of varying size. The gauging stations were chosen in different climatic regions, from glaciers in maritime climatic conditions on the west coast to glaciers in the continental parts of Eastern Jotunheimen. Furthermore, results will naturally be obtained from geologically different regions. The flow from these glaciers may possibly be harnessed for future energy production, and the choice was therefore guided by this possibility. Should abrasion occur as the result of the sediment content, the results of our studies may have direct importance for the evaluation of damage. Parallel to the studies of the total sediment transport, sedimentation in front of the glaciers is also studied. The quantity of sediment material in a lake of a certain size may be a guideline as to what measures have to be taken to remove most of the sediment from the river water.

The observation stations have been placed as close as possible to the glacial front, at a point where the melt water is contained in one channel. A staff gauge and/or stage recorder and a small cabin for two observers have been erected at each gauging site. The stations are manned 3 to 4 months during summer, usually by students. They collect 5 to 6

daily samples to determine the sediment concentration, and they also collect samples every hour during rapidly increasing or flood discharges. At most stations, meteorological and glaciological observations are also carried out.

Sediment transport in glacial rivers may be, for simplifying purposes, divided into two main groups:

1. Suspended particles, and
2. Bed load transport.

Of these two, the former is usually most readily determined, whereas the bed load transport has proven to be almost impossible to determine directly. These investigations have concentrated on measurement of the load of suspended material and its sedimentation in still waters where such waters are found. Because bed load materials may cause difficulties at tunnel intakes, attempts have been made to measure the amount of such material. A net has therefore been placed across the river from Nigardsvatn Glacier for volume evaluation of the delta produced. Similar investigations are pursued at Vesledalsvatn Glacier and have been started at Engabrevatn Glacier.

We have reason to believe that these very detailed investigations will give a good picture of the total sediment transport from each of the glaciers that have been studied. Similar studies are performed at glaciers of a different type and a different climatic and geological condition. Comparisons and conclusions regarding glacial erosion may therefore be conducted on a representative basis. These studies are strengthened by other related investigations near the studied glaciers (ablations and accretions, precipitation and meteorological observations). The reasons for varying sediment transport at each glacier and between glaciers in different areas may thereby be investigated.



## SEDIMENTATION STUDIES AND EVALUATION METHODS

Sedimentation Studies

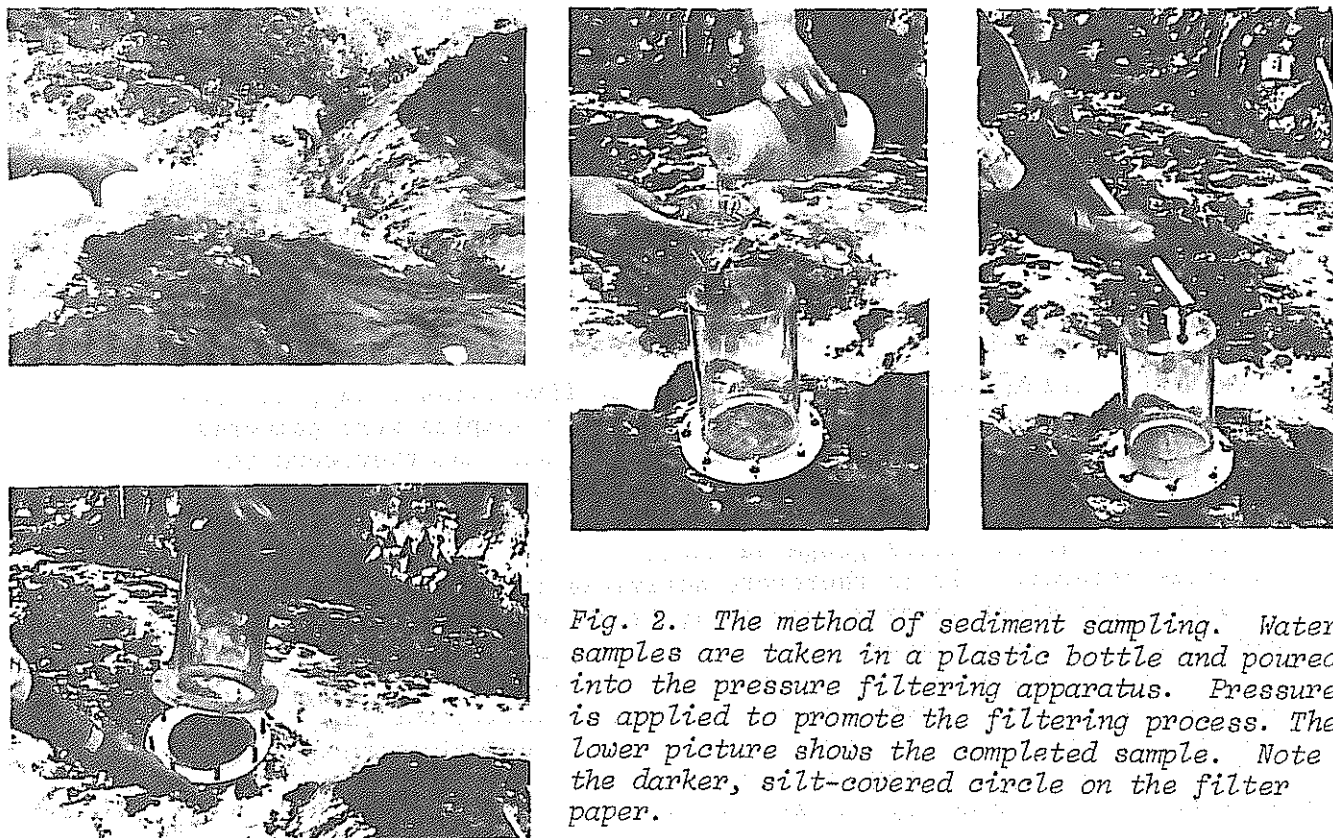
Sedimentation studies were conducted in the summer of 1969 at five selected glaciers: Nigardsbreen, Vesladalsbreen, Engabreen, Erdalsbreen and Memurubreen. At the latter two glaciers, samples were gathered at only one point in the river. At the former three glaciers, samples were also taken at the outlet of the natural sedimentation basins built by the lakes in front of the glaciers.

Field Measurements

Sediment samples were usually taken two to five times a day, depending on manpower and the local conditions. Water samples were gathered in plastic bottles approximately 1 liter in volume, and they were immediately filtered through a pressure-filtering apparatus (Fig. 2). For every sample, the time and water level were observed. At the lakes, it is important that the staff gauge be close to the outlet, usually next to a stage recorder. It is therefore advisable to note that because of wave action the staff gauge readings may be uneven compared with the stage recorder registrations; e.g., the conditions at Nigardsvatn, where the prevailing wind direction is from the east with an approximately 2-km staff gauge measurement is from 2-4 cm. Similar, but far lesser, errors may be found at the other staff gauges. An evaluation of the influence of different errors on the final result has been conducted in a separate part of this report (see below).

During rapidly increasing discharges so-called 24-hour series were conducted. Samples were collected every hour in the glacial river and, if at all possible, even at the outlet of the lake. These hourly samplings were discontinued if the flood discharges culminated by midnight. If not, they were continued until such was the case. This was a burden on the observers, but the influence of a single flood on the total sediment transport is so great that it was necessary to conduct the sampling in this manner. As an example, during one single 24-hour period in 1969 approximately 10 percent of the total observed sediment transport passed by Nigardsbreen (the whole measuring season comprised 94 days).

After filtering and drying, the samples are forwarded to Oslo for laboratory investigations. Sample sediment masses were determined by burning the filtering paper and carefully weighing the remaining sediment material. Details of the laboratory process have been described by Østrem and Stanley (1969, p. 59-60) and Tornas (1969, p. 101-102).



*Fig. 2. The method of sediment sampling. Water samples are taken in a plastic bottle and poured into the pressure filtering apparatus. Pressure is applied to promote the filtering process. The lower picture shows the completed sample. Note the darker, silt-covered circle on the filter paper.*

#### Calculation of Error

In those cases where sediment samples were taken both at the glacier front and at the inlet to a lake in front of the glacier, the discharge at both points has had to be estimated on the basis of water level readings (staff gauge and stage recorder) at the outlet of the lake. Unfortunately, technical reasons made it impossible to install gauges at both the inflow and the outflow of the lake, and the results for 1968 may therefore include errors, especially for the calculation of the discharge into the lake (i.e., in the glacial river). For 1969, corrections have been made as described below.

The discharge in the glacial river and at the lake outlet often differ, as we know. This depends on whether the water level in the lake is increasing or decreasing and whether there has been any precipitation

in the area. Because there usually is a relatively larger sediment transport when the discharge is increasing than when it is decreasing, the sediment transport in the lake may be calculated too low if the water storage in the lake is not taken into account. The nomograph in Fig. 3 is based on Nigardsvatn's total surface area of  $0.46 \times 10^6 \text{ m}^2$  and a catchment area of  $9.2 \times 10^6 \text{ m}^2$  between the sample points. Thus the lake inflow is based on the following equation:

$$Q_i = Q_u + \frac{S_1 \times a}{0.36 \times 10^6} - \frac{S_2 \times p}{3.6 \times 10^6},$$

where:

- $Q_i$  = the unknown discharge of the glacial rivers, in  $\text{m}^3/\text{s}$ ;
- $Q_u$  = the known discharge at the outlet, in  $\text{m}^3/\text{s}$ ;
- $S_1$  = the lake surface area, in  $\text{m}^2$ ;
- $S_2$  = the catchment area between inlet and outlet points, in  $\text{m}^2$ ;
- $a$  = the gradient on the stage recorder curve, in  $\text{cm/h}$  (+ or -); and
- $p$  = precipitation, in  $\text{mm/h}$ .

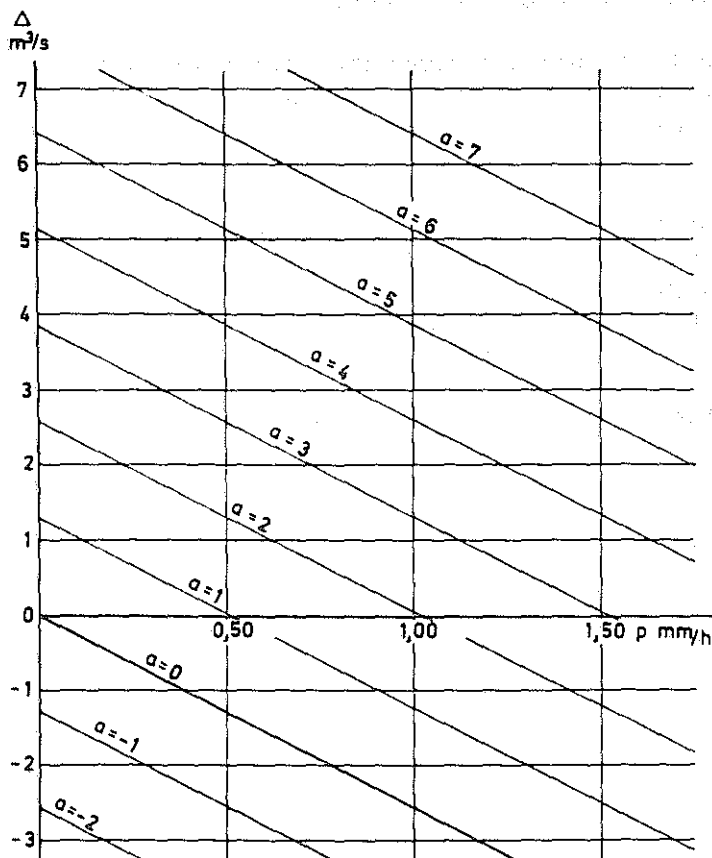


Fig. 3. Nomogram for the determination of the discharge into Lake Nigardsvatn. The nomogram shows the relation between runoff into Lake Nigardsvatn, discharge from the lake, rising or falling water level, and precipitation.

Example: Increasing water level 2  $\text{cm/h}$  ( $a = +2$ ) precipitation 12  $\text{mm}$  per day ( $p = 0.5$ ). The intersection between the lines  $a = +2$  and  $p = 0.5$  gives the value  $\Delta = 1.4 \text{ m}^3/\text{s}$ , which means that water into the lake is  $1.4 \text{ m}^3/\text{s}$  higher than out of the lake.

From the preceding equation and the nomograph, it may be seen that the precipitation will reduce the difference between the water discharge into and out of the lake at increasing water level. Because the combination of decreasing water level and precipitation rarely occurs and probably adds no noticeable error to calculations of sedimentation, the lower part of the nomograph is of little interest. The nomograph clearly shows that large errors may occur if precipitation and storage are not taken into account. As an example, a not unusual value of "a" is 2 cm/h, (values of up to +9 cm/h have been registered in Nigardsvatn), and this implies that the water discharge to the lake is  $2.6 \text{ m}^3/\text{s}$  larger than the outflow from the lake during periods of no precipitation; if it rains, the figure will be lower. ( $a = 9$  implies that  $Q_i = Q_u + 11.52 \text{ m}^3/\text{s}$ ). The difference in sediment transport with or without the aforementioned corrections may therefore be up to 30 percent or more for separate hourly values.

Another error source of calculating sediment transport is introduced by the fall flood which often takes place after the observations have been terminated. Very often floods will take place in September or October in the rivers on the west coast of Norway. Since sediment samples usually are not collected at this late date, one has no record of how much unaccounted for sediment material has passed. It is therefore obvious that the observation period should be lengthened to include several more weeks in September, as the fall flood usually takes place within this period (see Fig. 4). Furthermore, an agreement should be reached with the local people to record later unexpected floods.

Normally, the fall floods seem to be smaller than the larger summer floods, so the quantity of transported material will probably be of a smaller amount. Exceptions from this may occur, however, (e.g., the year of 1962).

Regarding the accuracy of the measurements in 1969, there are of course also other sources of errors, some of them difficult to evaluate. The measuring period comprises only a part of the year; the discharge equation may include errors; uncertainty in the readings of the stage recorder may have an influence, etc. The dominating source of error is, however, quite probably, the sampling of sediment material in itself, and with the many steps in calculation of the amount of sediment material per hour, day, or year.

The first part, the sampling, comprises sources of error concerning the volume of the sample (approximately 1 liter). It is of course of utmost importance whether one sample may be said to be representative of the total river cross-section at the gauging station. A limited investigation of these conditions in turbulent water was carried out in 1961 at Tarfalajokk, Kebnekaise (Ahlbert and Sjøberg, 1962, p. 13-14). In this investigation an approximately 10 percent higher sediment content was found in samples taken at the bottom, as compared to those taken at the surface. Samples taken at the edge of the river gave an approximate 3 percent higher value than those taken in the middle of the river. Unfortunately, there is no knowledge of the depth at which the samples were taken nor of whether bed load material may have influenced

## NIGARDSVATNET

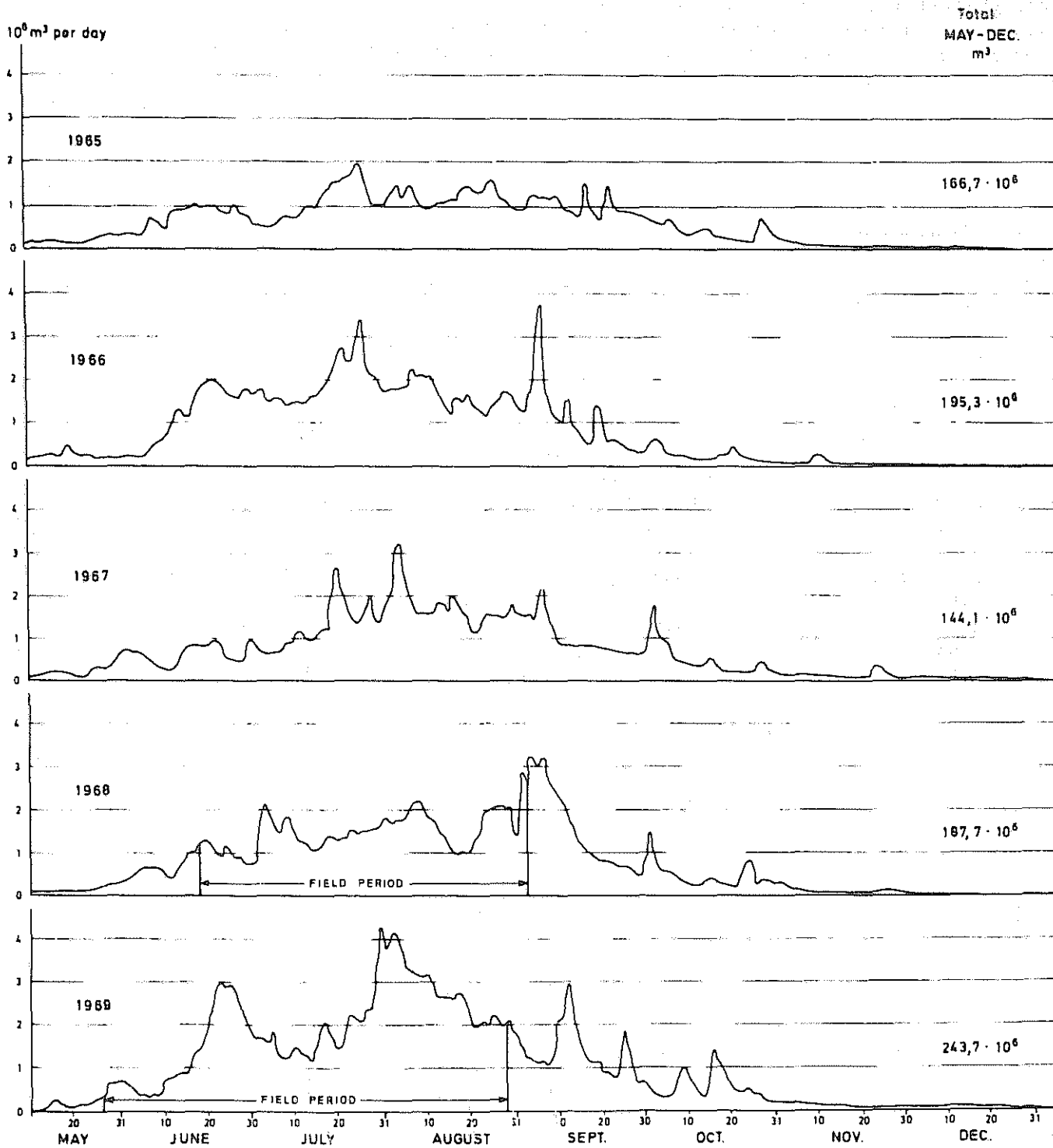
WATER DISCHARGE  
1965 - 1969

Fig. 4. Water discharge from Lake Nigardsvatn, 1965-1969

the result. A similar investigation in the same river was carried out in 1969, this time in a flume, which gave a more uniform current (Elg and Gustavsson, 1970). The investigation gave a somewhat confusing result with differences between different measuring points in the cross section of the flume of up to 80 percent of the maximum value. If this result is significant for a glacial river, it is obvious that samples from one point of the cross section are of no value.

The situation at Nigardsvatn, Vesladalsvatn and the lake in front of Engrabreen can, however, not directly be compared to the constructed flume at Tarfalajokk. The flow at the gauging stations at both ends of the Norwegian lakes is clearly turbulent and may not be compared to the situation for the above mentioned flume which also has a form and a location in relation to the river which gives the flow an unusual character with standing waves, etc.

Even if the situation at the above mentioned lakes is closer to the investigation in Tarfalajokk in 1961 (before the constructed flume), it will still be necessary to have a systematical investigation of the sediment variations in the river cross-sections at the gauging stations. Further, if it is found that one measuring point is representative, double samples should be taken in each case. This would provide an easier control of errors that might exist in the further investigation of the sample.

For the final test of the sample, burning and weighing in the laboratory, it is rather simple to determine the relative importance of the sources of error, and the present method has been described as satisfactory. An estimate of the error in the laboratory procedure is derived below where M equals the quantity of sediment material per day, given in kilograms:

$$M = \frac{m}{V} \times A(H-h)^B \times 3.6$$

$$(Q = A(H-h)^B \text{ is the equation for the discharge rating curve})$$

where:

m = difference in weight before and after burning, in mg;

V = volume of the sample, in liters;

A, B, H = constant values; and

H = the staff gauge reading, in cm.

Through logarithmic differentiation, an equation is obtained of the form:

$$\frac{\partial M}{M} = \frac{\partial m}{m} - \frac{\partial V}{V} + B \frac{\partial(H-h)}{H-h}$$

and transforming to standard mean error gives:

$$\left(\frac{s_M}{M}\right)^2 + \left(\frac{s_m}{m}\right)^2 + \left(\frac{s_V}{V}\right)^2 + \left(\frac{B \cdot s_{H-h}}{H-h}\right)^2$$

As an example, this formula, for real chosen values, is illustrated by data from two different days during the summer of 1969:

Example 1. June 13 (normal day)

Accepted errors

|                 |                                 |
|-----------------|---------------------------------|
| H = 140 cm      | + 0.5 cm (reading error)        |
| h = 13 cm       | + 0.0                           |
| m = 8.99 mg     | + 0.1 mg (weighing error)       |
| V = 1.000 liter | + 0.010 liter (measuring error) |

Inserting these values in the above formula will give

$$\left(\frac{s_M}{M}\right)^2 = 0.0001 + 0.0001 + 0.0001 = 0.0003$$

$$\left(\frac{s_M}{M}\right) = 0.017 \text{ or } \underline{\text{approximately 1.7 percent error in M}}$$

Example 2. July 31, 1969 (increasing high water level)

|                 |
|-----------------|
| H = 237 cm      |
| h = 13 cm       |
| m = 48.53 mg    |
| V = 1.000 liter |

With the same presumed errors for H, m and V we get

$$\left(\frac{s_M}{M}\right)^2 = 0.000004 + 0.0001 + 0.000036 = 0.000140$$

$$\left(\frac{s_M}{M}\right) = 0.012 \text{ or } \underline{\text{approximately 1.2 percent error in M}}$$

This proves that the inaccuracy in weighing means relatively little for the determination of M, which is the total quantity of transported sediment material per day. It is, therefore, clear that other sources of error, especially conditions during sampling ought to be investigated further. Sampling errors will be given particular consideration during the field work that is planned for the summer of 1970.

Data Evaluation of Sediment Transport and Water Transport

During the fall of 1969, a program was worked out for automatic data processing of sediment and discharge measurements. Work was performed by J. Anderson, a state hydrologist, at the Institute of Water Resources,





### Output Data

The computer gives the following results (Fig. 6):

#### Printout (one day per page)

each hour:    water level  
                  water discharge, outlet  
                  water discharge, glacial river (inflow to lake; ed.)  
                  quantity of sediment material, outlet  
                  quantity of sediment material, glacial river  
    (inflow; ed.)

each day:    sediment discharge at outlet, tons/day  
                  water discharge at outlet, m<sup>3</sup>/day  
                  sediment transport glacial river, tons/day  
                  water transport glacial river, million m<sup>3</sup>/day

(For Erdalsbreen and Memurubreen, where the samples were taken at one point only, the printout will have a simpler form since all data "out of the lake" are absent.)

Since most of the computer time is spent on printouts, it is quite unnecessary to print all hourly values for every day. It is, however, valuable to have these printouts during an investigation in order to be able to discover print errors or obvious measurement errors.

We intend to include one more part to the program to directly print out a graphic form showing the sediment load versus time.

An example of a punchcard pertaining to one hour is shown in Fig. 5. It is obvious that all data should be tabulated for the observation stations so as to make them easy to read by the punchcard operator. One should also attempt to perform sampling at whole hours to facilitate the inclusion of the input data to the computer program.

Data processing of this kind is a great timesaving device and eliminates many sources of error that would be introduced by manual processing.

## SLAMBEREGNINGER

NIGARDSBREEN VMNR. 1408 KODE. 0

DATO. 17/ 7 AAR. 1969

| KL                   | 1        | 2      | 3         | 4      | 5       | 6      | 7     | 8            | 9     | 10    | 11    | 12     |
|----------------------|----------|--------|-----------|--------|---------|--------|-------|--------------|-------|-------|-------|--------|
| VST. (M)             | 1.90     | 1.89   | 1.88      | 1.89   | 1.86    | 1.86   | 1.86  | 1.86         | 1.86  | 1.87  | 1.87  | 1.89   |
| VF. (M3/S)           | 23.83    | 23.46  | 23.10     | 23.46  | 22.39   | 22.39  | 22.39 | 22.39        | 22.39 | 22.74 | 22.74 | 23.46  |
| TS. (M3/S)           | 22.55    | 22.19  | 23.10     | 22.19  | 20.47   | 22.39  | 22.39 | 22.39        | 23.03 | 23.38 | 24.02 | 26.66  |
| NEDBOR (MM)          | -        | -      | -         | -      | -       | -      | -     | -            | -     | -     | -     | -      |
| MU. (MG/L)           | 25.44    | 28.12  | 30.80     | 33.48  | 36.15   | 38.83  | 41.51 | 38.61        | 35.71 | 32.81 | 29.91 | 27.00  |
| MU (TONN/T)          | 2.18     | 2.38   | 2.56      | 2.83   | 2.91    | 3.13   | 3.35  | 3.11         | 2.88  | 2.69  | 2.45  | 2.28   |
| MI. (MG/L)           | 100.78   | 98.10  | 95.43     | 92.76  | 90.08   | 87.41  | 84.73 | 82.06        | 87.91 | 93.77 | 99.62 | 250.38 |
| MI (TONN/T)          | 8.18     | 7.84   | 7.94      | 7.41   | 6.64    | 7.05   | 6.83  | 6.61         | 7.29  | 7.89  | 8.62  | 24.03  |
| KL                   | 13       | 14     | 15        | 16     | 17      | 18     | 19    | 20           | 21    | 22    | 23    | 24     |
| VST. (M)             | 1.92     | 1.93   | 1.94      | 1.94   | 1.94    | 1.95   | 1.95  | 1.94         | 1.94  | 1.94  | 1.93  | 1.91   |
| VF. (M3/S)           | 24.57    | 24.94  | 25.32     | 25.32  | 25.32   | 25.71  | 25.71 | 25.32        | 25.32 | 25.32 | 24.94 | 24.20  |
| TS. (M3/S)           | 27.12    | 26.22  | 25.96     | 25.32  | 25.96   | 26.34  | 25.07 | 24.68        | 25.32 | 24.68 | 23.03 | 22.28  |
| NEDBOR (MM)          | -        | -      | -         | -      | -       | -      | 1.10  | -            | -     | -     | -     | -      |
| MU. (MG/L)           | 24.10    | 21.20  | 18.30     | 16.42  | 14.53   | 21.38  | 28.22 | 24.91        | 21.59 | 18.27 | 14.95 | 14.84  |
| MU (TONN/T)          | 2.13     | 1.90   | 1.67      | 1.50   | 1.32    | 1.98   | 2.61  | 2.27         | 1.97  | 1.67  | 1.34  | 1.29   |
| MI. (MG/L)           | 222.14   | 193.89 | 165.64    | 137.39 | 109.14  | 80.89  | 52.64 | 52.62        | 52.60 | 52.59 | 52.57 | 52.55  |
| MI (TONN/T)          | 21.69    | 18.30  | 15.48     | 12.52  | 10.20   | 7.67   | 4.75  | 4.68         | 4.80  | 4.67  | 4.36  | 4.21   |
| SLAMFORING. (AVLOP)  | 54.3982  |        | TONN/DOGN |        | AVLOP.  | 2.0763 |       | MILL.M3/DOGN |       |       |       |        |
| SLAMFORING. (TILSIG) | 219.6556 |        | TONN/DOGN |        | TILSIG. | 2.0763 |       | MILL.M3/DOGN |       |       |       |        |
| KORRIGERT FUR NEDBOR | 218.6066 |        |           |        |         | 2.0662 |       |              |       |       |       |        |

Fig. 6. Sample output data sheet

## SEDIMENT TRANSPORT IN CHOSEN GLACIAL RIVERS

## WITH NATURAL SEDIMENTATION BASINS

The investigations started at Nigardsvatn and Vesledalsvatn in 1968, were continued in 1969, and a new one was started at Engabreen. The work comprised mainly measurements of sediment transport in and out of the lakes, and for the two former, measurements of the natural formation of the delta. The work was performed by the Institute of Water Resources in Oslo and the Institute of Natural Geography at Stockholm University. The project was and is administered by Dr. G. Østrem, funded by the above mentioned institutes, while S. R. Ekman was mainly in charge of the field work. The investigation program for 1969 consisted in general of three main parts:

1. Water discharge and sediment volume measurements in glacial rivers above the lakes and at the outlet of the lakes. The sedimentation of fine material on the bottom of the lakes may thereby be calculated.
2. Investigation of the natural growth of the delta at the inlet to the lake. This part of the program was mainly performed in the inner part of Nigardsvatn. Similar but less frequent measurements were performed in Vesledalsvatn; however, the delta in the lake in front of Engabreen has not been investigated yet.
3. Development of sampling routines with the intention of evaluating the results by computed processing of the data.

NigardsbreenThe Net Project at Nigardsbreen to Measure the Bed Load in the Glacial River

The ability of a glacial river to move great quantities of material by bed load transport is well known from a qualitative point of view. Thus, the glacial river at Nigardsvatn is building up a delta in the lake which contains great quantities of coarse material up to boulder size (Fig. 7). It is easy to ascertain that the bed load transport is large in the river from the glacier to the delta, among other things, from the amount of noise made by the moving rocks.

The bed load transport is certainly of great importance for decisions relative to whether the lake close to the glacial river is suitable as a sedimentation basin for a power station, for instance.

Even if it is quite simple to perform qualitative analysis of the bed load material transported in a river, substantial problems are encountered in quantitative calculations.

A large number of sample apparatus for bed load transport have been described in the literature, and these are all more or less of intricate construction (for instance, see Hubbell, 1963). Further, many attempts

have been made on theoretical calculations (for instance, Leopold, *et al.*, 1964).

The theoretical formulas contain some weaknesses, especially because the number of parameters in such equations is very large; there are far too many factors influencing the bed load transport to make it possible to use general formulas.



*Fig. 7. The net at the inlet to Lake Nigardsvatn with accumulated coarse sediments. In the background a part of the developing delta can be seen.*

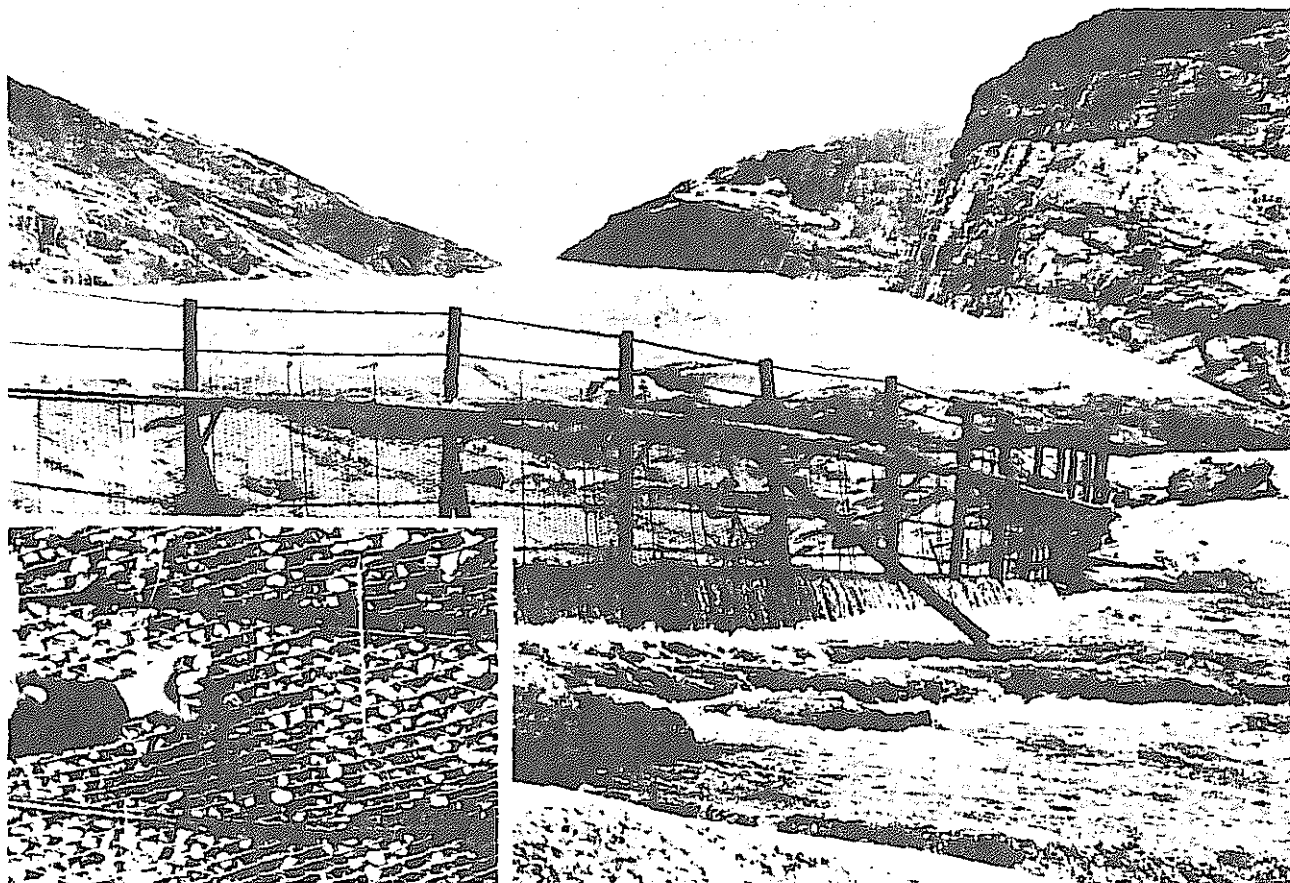
The sample apparatus are usually limited by giving only point test results, and these may hardly be said to be significant for the total transport, or they will influence the flow in the river and the measured results will therefore not be representative for the natural conditions.

One may possibly expect that the relation between bed load transport and suspended sediment transport may have a constant value for glacial rivers in similar bedrock areas.

With the intention of studying bed load phenomena through a new method, the so-called "net project" was tried at Nigardsvatn in 1969.

The net (Fig. 8), an especially constructed steel wire net of mesh size 2 x 6 cm, was erected across the river cross-section at a convenient point, approximately half way between the glacier snout and the

lake. The height of the net was 2.5 m, and the length from shore to shore was approximately 50 m. The net was held up by rail bars strengthened by steel bolts in the bed rock. Drilling could unfortunately not be done over the whole profile due to loose materials in the southern part of the cross-section. These loose materials were of such thickness that one could not easily drill down to the bed rock. Experience showed, however, that this should have been done. The net was held in place with heavy steel cables, anchored to bolts in the rock (see Figs. 8 and 9). This work was performed in May 1969 under the management of O. Fredriksen of the Institute of Water Resources, and the net was finished May 24.



*Fig. 8. The net with the glacier front of Nigardsbreen in the background. The difference in water levels in front of and behind the net demonstrates clearly the amount of accumulated material. A detail of the net (insert) shows uniform captured material.*

The measuring method: The bed load accretion within the fence area was determined through surveying parallel profiles. This was accomplished by dividing the area upstream from the fence with steel wires arranged in squares of 2 x 2 m. Thus, two parallel lines were stretched between the points F-0 and F-46 and also between K-0 and K-46 (Fig. 9). Further, lines marked with colors were stretched between the fence and the wire K-K via wire F-F. This way approximately 180 fixed measuring points were designated within the fence area. These were surveyed six times during the life time of the fence using the point F-0 as a reference. A surveyor level (Wild M 10) was used with the usual levelling rod. The fixed point for all measurements was F-0, which was arbitrarily set to 10.00 m.

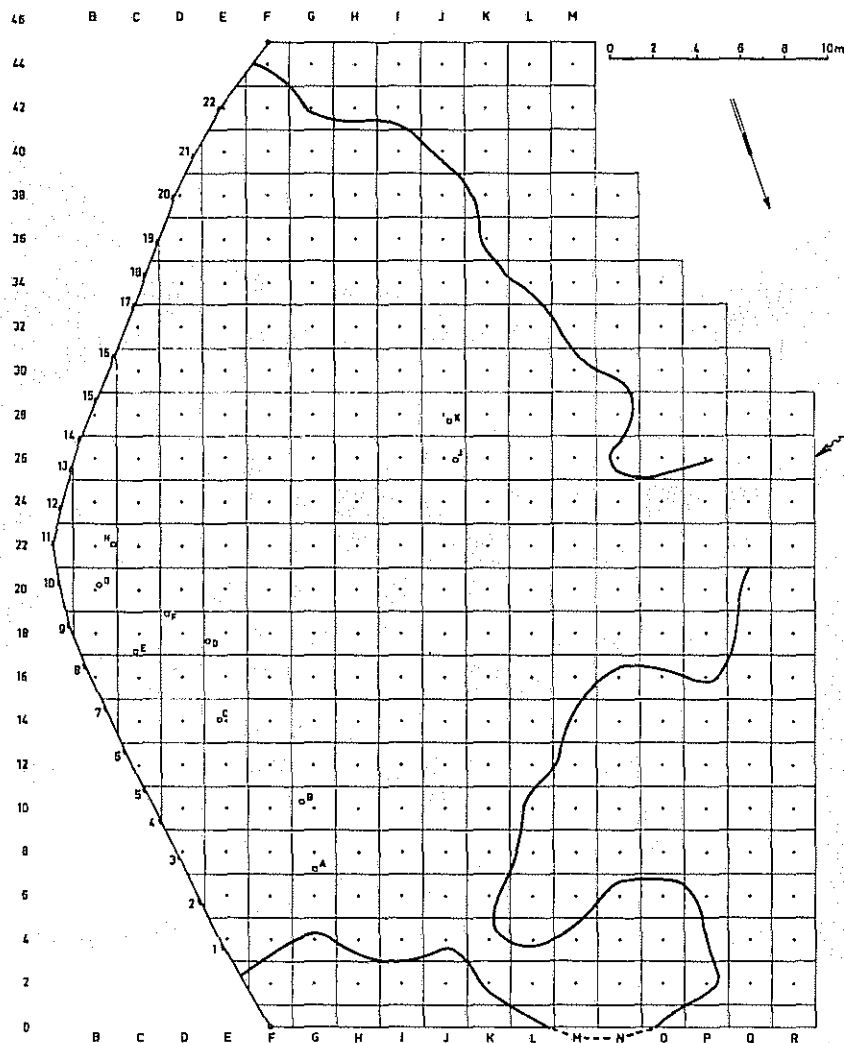


Fig. 9. Map showing the net and net area. Control stakes (A-K) are mounted in the bedrock. The heavy line is the local level of 9.00 meters in a system where F-0 is 10.00 meters.

It may be noted that this method provides a very good and quick volume determination even if it is not quite without risk for the person handling the levelling rod. The 180 measuring points cover an area of 720 m<sup>2</sup>. The total area could not be surveyed in all cases due to heavy currents, especially in and around O-22, but most of the points were surveyed regularly.

As mentioned, the net was ready on May 24. During a heavy flood in the latter part of June, the net was loosened from the bottom in the southern part and caused material to suddenly break loose. Through this leakage point, material continued to be transported when the river's main stream was flowing in this direction through its meandering in the net area. The net was therefore opened between the stakes 8 and 9 on July 16, and on July 19 the whole net was broken down.

Experiences from the net project: Even with the relatively short time the net project was worked on, much experience was accumulated as to how such a project should have been performed. Generally, the investigation gave positive results, and it will be possible through this method to ascertain the quantity of material in bed load transport even over a longer period. The largest discharge of the season reached approximately 60 m<sup>3</sup>/sec, and this ought to be possible to handle. The net would have to be changed somewhat in its construction. It must be fastened to the rock bottom in all points, and the vertical stakes must be strongly supported from the bottom up, and even the supporters must be bolted. At some points, the stakes should also be strengthened by strong wires.

The most serious problem in 1969 was, however, the large quantities of ice that were transported in the river in the latter part of the season. This ice transport was expected, but not in such great quantities, and it was actually the ice which caused the net to break on July 19. The ice acts on the net differently from rocks and blocks. It has higher velocity on contact, and since it floats, it has a much greater influence on the durability of the net. The ice, therefore, has to be stopped before it reaches the net, and this should be possible through the erection of some stakes above the net, for instance.

Results: In the period from May 24 to June 19, an accumulation of 398 metric tons of material was measured within the net area. This value was obtained through a measured volume of about 200 m<sup>3</sup> and an average specific weight of 2000 kg/m<sup>3</sup>, obtained through samples taken in different parts of the accumulation area. During the same period, a suspended sediment transport of 1276 metric tons was measured.

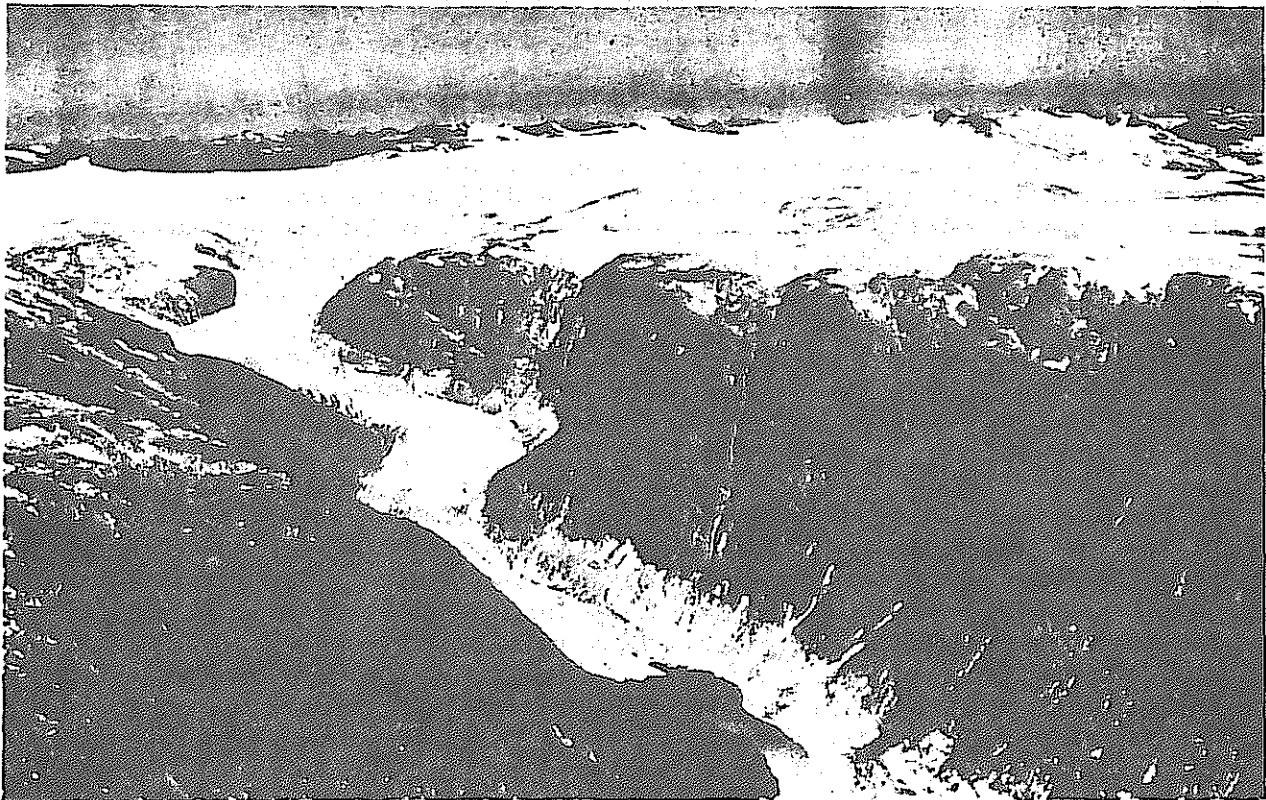
The ratio between the bed load transport material and the suspended transport material is therefore approximately 30 percent. This value is definitely a minimum since the mesh of the net allows a great part of the fractions between 1 mm and 20 mm to pass the net area. All of these fractions are not lost, however. Through digging in the material behind the net it was found that large quantities of fine sediment material had been covered by coarser material.

It may be said with certainty that over the period studied at least

25 per cent of the sediment transport in the river took place as bed load transport (and probably a lot more). The remaining transport, 75 percent of the total, was suspended material and particles in the size fraction 1-20 mm.

#### Sedimentation Studies in Nigardsvatn

Over the last 30-40 years, the glacier Nigardsbreen has produced a lake immediately in front, Nigardsvatn Lake.



*Fig. 10. Photograph of Nigardsbreen draining from the Jostedalsgreen ice cap taken in 1954. At that time the outlet glacier extended right into Lake Nigardsvatn. The lighter zone in the valley bottom indicates a former stage of this glacier (approx. 1750 A. D.).*



## A few facts about Nigardsvatn Lake:

|  |                                |
|--|--------------------------------|
| Length   | about 1800 m                   |
| Greatest width   | about 380 m                    |
| Surface area at reference level (water level = 150 cm) | $0.46 \times 10^6 \text{ m}^2$ |
| Greatest depth   | 34 m                           |
| Volume at reference level                              | $5.4 \times 10^6 \text{ m}^3$  |
| Height above sea level                                 | 285 m                          |
| Catchment area between inflow and outflow              | $9.2 \times 10^6 \text{ m}^2$  |
| Total catchment area at the outflow                    | $64 \times 10^6 \text{ m}^2$   |
| Area covered by Nigardsvatn glacier                    | $47 \times 10^6 \text{ m}^2$   |

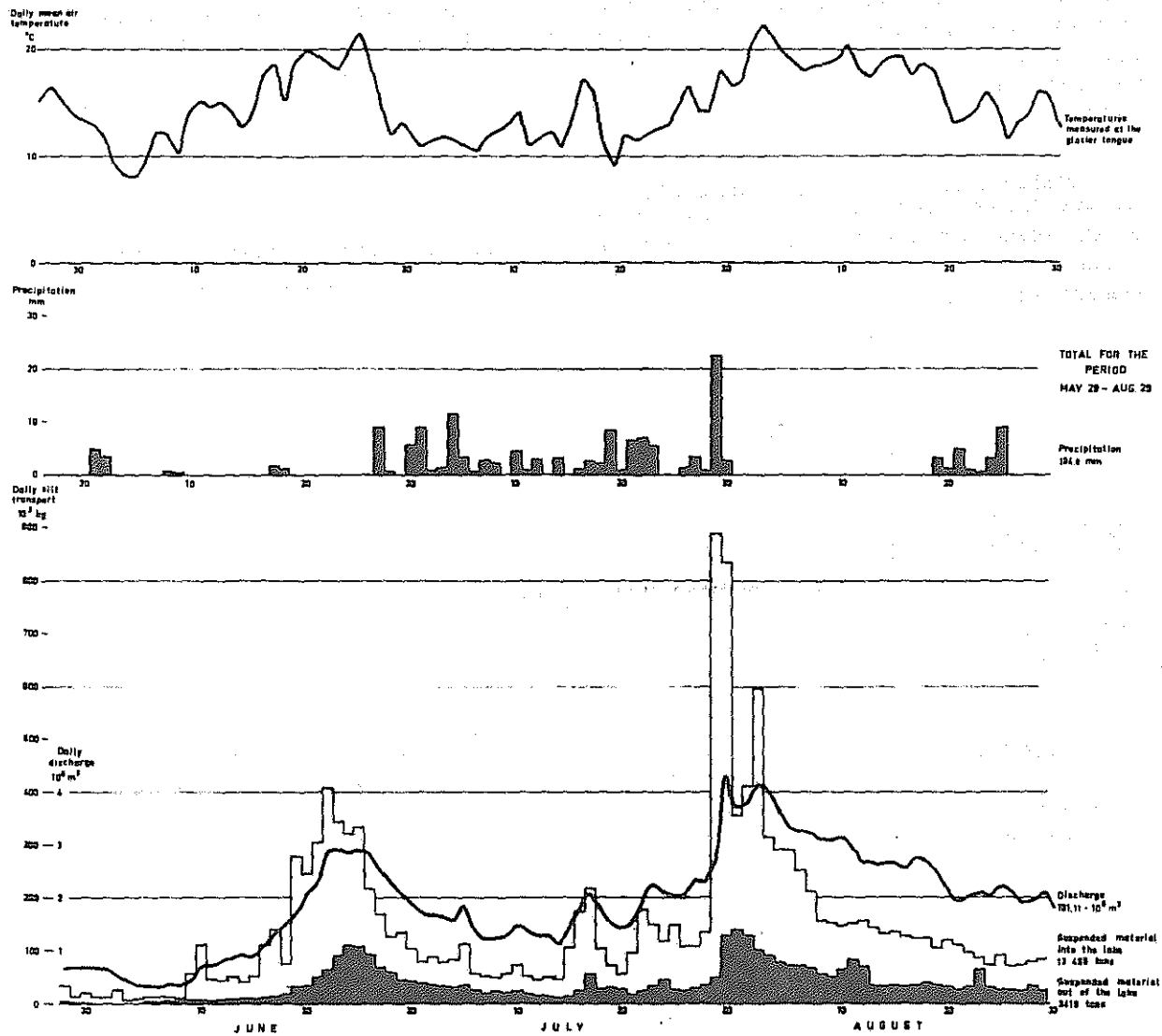


Fig. 11. Sediment transport and meteorological observations at Nigardsvatn in 1969.

Sediment studies in 1969: The field work period of 1969 covers May 27 to August 30. At the testing site on the glacial river immediately below the glacier snout, 13,910 metric tons of suspended material passed during the observation period (94 days). During the same period, 3,440 metric tons were transported out of the lake. Thus, 10,470 metric tons remained in the lake (Fig. 11).

As may be seen from the above discussion on bed load transport, one may assume that practically all of the bed load material was accumulated in the lake. The total volume of water which passed the lake during this period was  $183.2 \times 10^6 \text{ m}^3$ .

Tornås (1969, p. 118) gave the following data for the summer of 1968: 4,370 metric tons of suspended material were carried into the lake and 1,375 metric tons of suspended material were carried out of the lake. The data for 1962 (Wehn, 1965, p. 60) were 2,530 metric tons into and 728 metric tons out of the lake. The 1962 data for the material transported into the lake have to be considered with some care since the glacier then extended into the lake, and a clearly defined river was not to be found at the time. The 1968 data for the sediment volume inflow and outflow for the lake are obviously too low.

Studies of the development of the delta: The accretion measurements in the inner basin were started in 1968. During the month of February, depth measurements through the ice were performed, and to these 16 profiles with more than 400 depth measuring points were added during the summer of 1968.

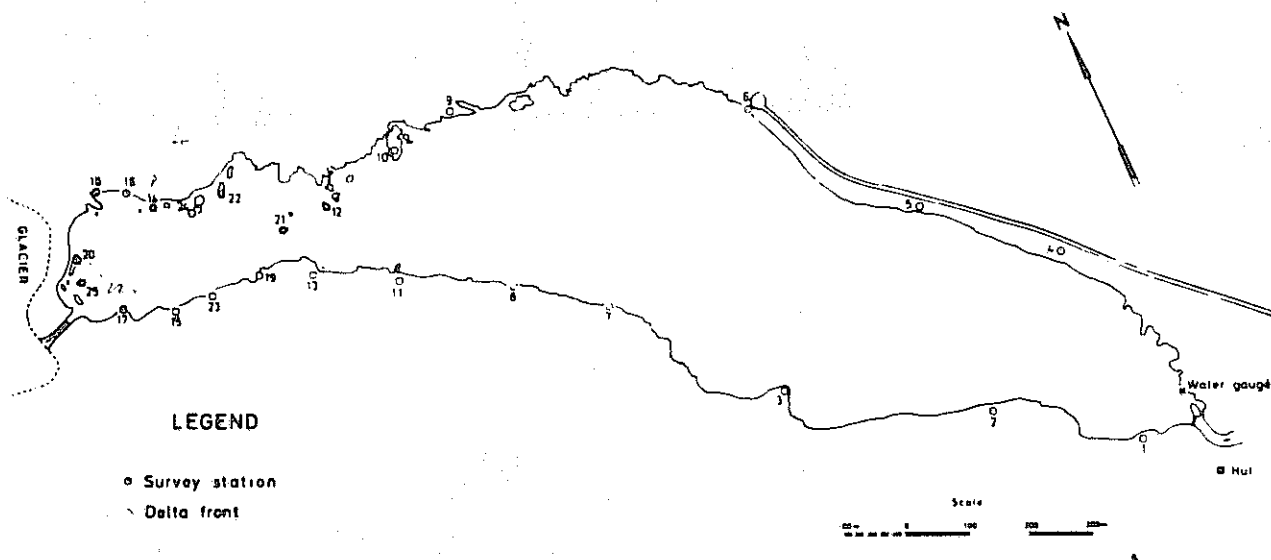


Fig. 12. Map of Lake Nigardsvatn.

The work in 1969 concentrated on 9 profiles with a total of 290 points. All these are situated west of the line 15-14 (Fig. 12), (i.e., in the inner part of the lake). The measuring lines for the other part of the "inner basin", (i.e., east of the line 15-14 to the line 10-11), showed no measurable sediment accretion. Measurements in this area will therefore have to be followed up over a longer period of time to give a usable result. The yearly accretion is obviously relatively small in this area.

The depth measurements were performed along steel wires which in each instance were stretched between the fixed points (noted in Fig. 12; ed.). These steel wires had earlier been measured and marked with colors at 5 meter intervals. The depth measurements were made by a regular leveling rod from a boat, which was moved along the wire. A depth measuring line and a measuring stick were used for greater depths. All measurements were attempted in calm weather in order to avoid bending the wire. (For each measurement, the wire carried no weight and the fixation of the points seems therefore to be quite accurate. The positions should be possible to repeat from year to year.) Staff gauge readings of the lake level were taken before and after each profile measurement at the gauge which was located at point 16. The water surface was further determined at point 20.

The uncertainty in the depth measurements is considered to be  $\pm 0.5$  cm. With a sharply sloping bottom, the uncertainty in the horizontal level may contain an error of one to a few centimeters in extreme cases. The accretion per year in the inner area is, however, so large that such errors are insignificant. In addition, the relative error is small enough to motivate acceptable conclusions regarding the volume of sediment accretions.

The depth of material has been noted on a map of the scale 1:500. The difference in the measurement values for 1968 and 1969 was noted with a special mark for each measuring point. Over this map was placed a transparent sheet with carefully drawn hexagons, each one covering an area of  $787 \text{ m}^2$ . The arithmetic mean value for all of the area within each hexagon was noted as representative of the area within the hexagon. The sum total of accumulated volume within the inner area of the basin (west of the line 15-14) gave  $4,778 \text{ m}^3$  or 9,576 metric tons. The total surface area is  $28,332 \text{ m}^2$ , which implies a mean accretion of 16.9 cm.

Even if these figures contain large errors, they give an idea as to the quantity of the sediment material in the inner basin. The measurements ought to give very dependable values for the total transport of coarse material from the glacial river, if they are carried out over some years.

#### Summary

From the above results it is concluded that, during the measurement period of 1969, 13,910 metric tons of suspended material were transported into the lake. At the net, approximately 400 metric tons of coarse material and in the delta approximately 9,500 metric tons of

sediment were accumulated. Even if these values have to be considered with some care, the results indicate that the bed load transport in the Nigard river is close to 50 per cent of the total transport. During the same period, 3,440 metric tons passed the lake outlet, and the total accumulation is therefore:

$$13,910 - 3,440 + 9,500 + 400 = \underline{20,370 \text{ metric tons}}$$

(disregarding the net)

This equals a volume of about  $10,000 \text{ m}^3$ , which may be compared to the total volume of the lake of about  $5,400,000 \text{ m}^3$ . (540 years will be necessary to completely fill the lake.) It should be noted that some of the suspended material is included in the accumulation in the basin and this has been measured through soundings.

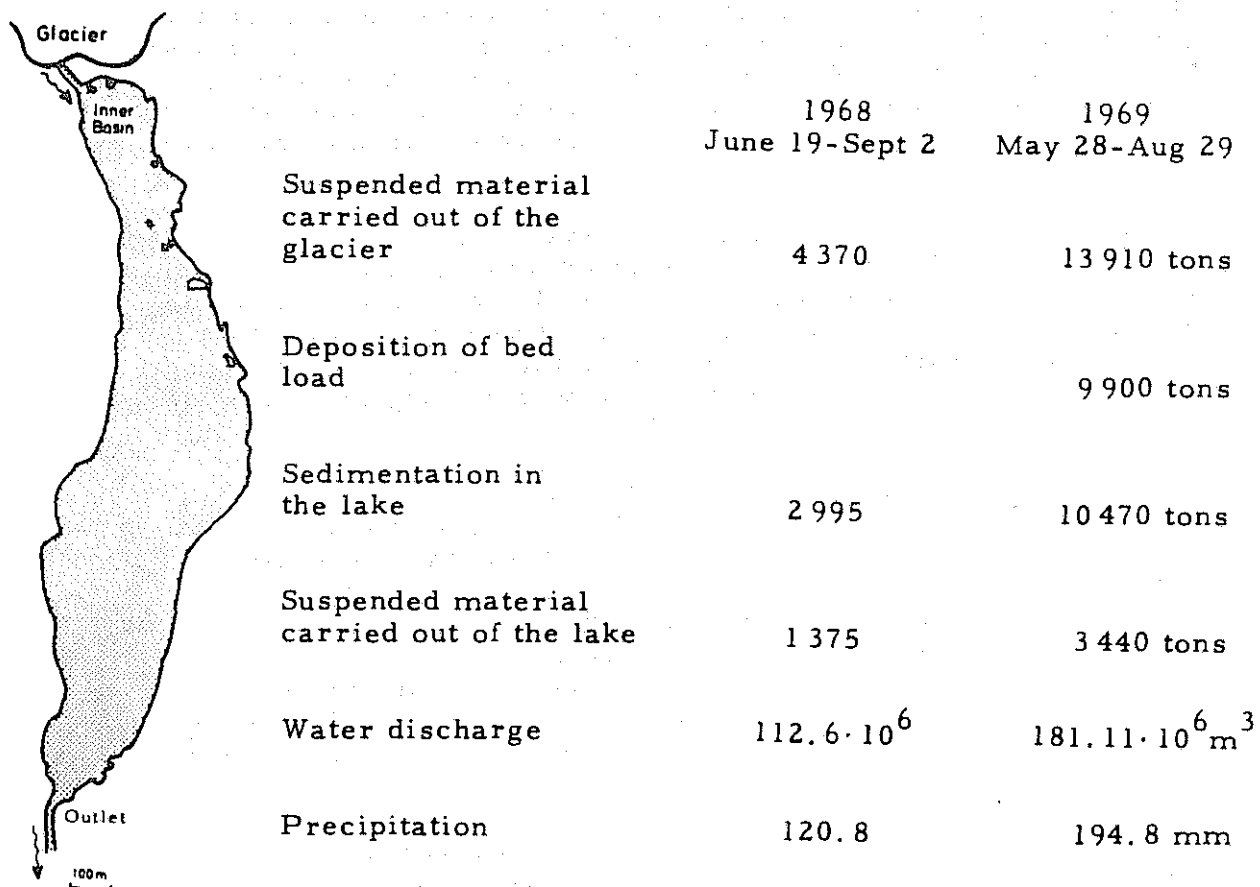


Fig. 13. Synopsis of the results for 1968 and 1969 at Nigardsvatn.

### Vesledalsbreen

Similar investigations to those performed at Nigardsbreen were performed at the waters leading from Vesledalsbreen during the field work season of 1969, with the exception of the net project, which was specific for Nigardsbreen.

Below Vesledalsbreen there is a natural sedimentation basin with a surface area of about 1800 m<sup>2</sup>. For this little lake soundings have been performed along fixed profiles, in order to calculate the accretion of coarse materials in the delta area. Simultaneously samples have been taken above and below the lake in order to determine the sediment transport by the glacial river.

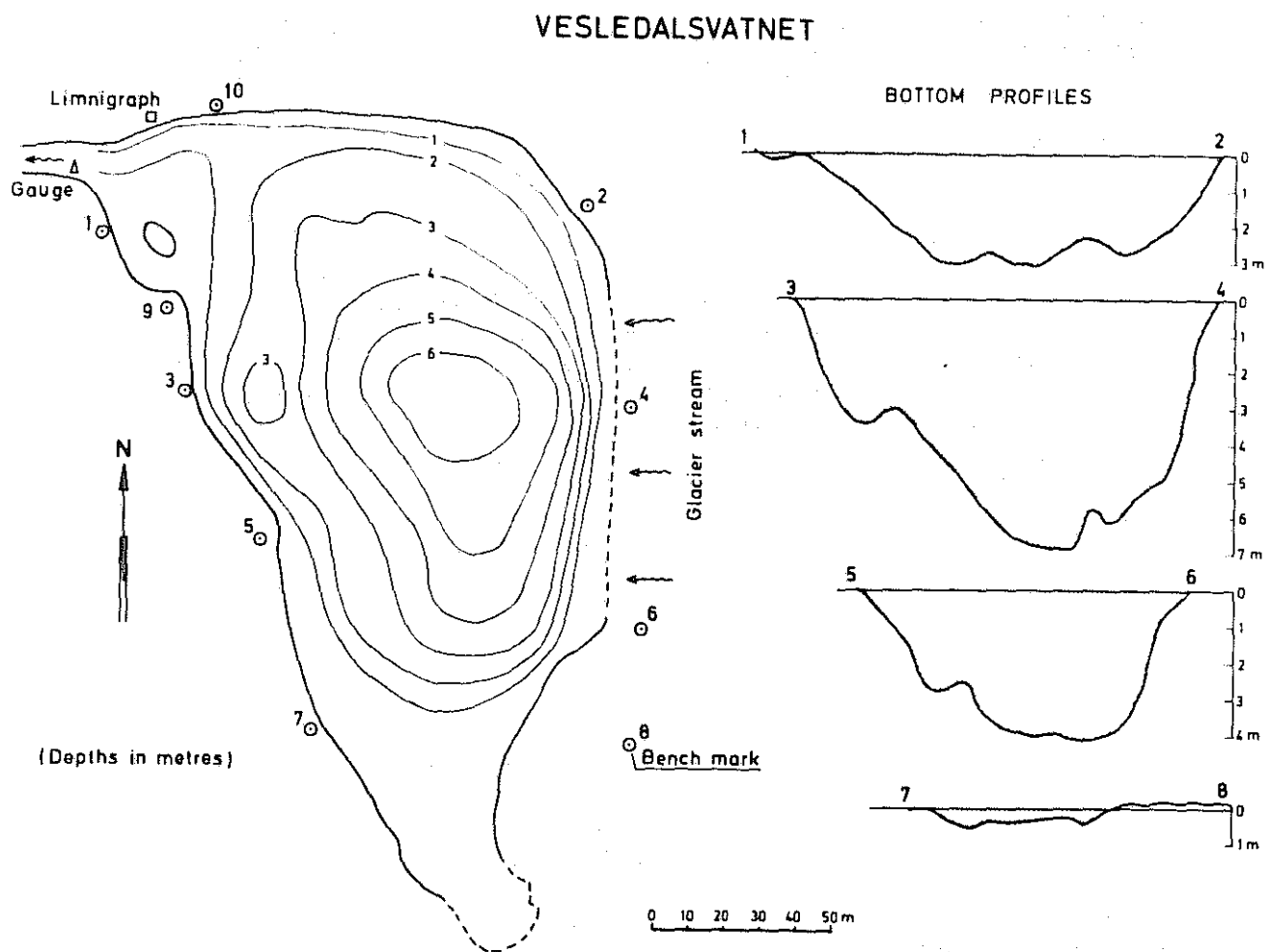


Fig. 14. Map and sounding profiles for accumulation measurements at Vesledalsvatn. On the map the location of bench marks and the sites of the staff gauge and water level recorder (Limnigraph) are plotted.

The difference between Nigardsbreen and Vesledalsbreen is mainly found in the topography and size. Both the glacier and the lake are much smaller in the case of Vesledalsbreen. There is a distance of approximately 1,000 m between the glacier and the lake at Vesledalen, and sediment samples were therefore taken both at the glacier front and at the inlet into the lake.

Some facts about Vesledalsvatn Lake:

|   |                                       |
|---|---------------------------------------|
| Length  | about 240 m                           |
| Width   | about 120 m                           |
| Surface area at reference level (162 cm on staff gauge) | 18,850 m <sup>2</sup>                 |
| Greatest depth  | 7 m                                   |
| Volume at reference level                               | 48,000 m <sup>3</sup>                 |
| Height above sea level                                  | 1,123 m                               |
| Catchment area at point A (Fig. 15)                     | 7.2 x 10 <sup>6</sup> m <sup>2</sup>  |
| B   | 9.2 x 10 <sup>6</sup> m <sup>2</sup>  |
| C   | 11.2 x 10 <sup>6</sup> m <sup>2</sup> |
| Area covered by glacier                                 | 4.0 x 10 <sup>6</sup> m <sup>2</sup>  |

Vesledalsvatn is quite shallow. The southern end has a flat bottom with a depth of about 0.5 m (Fig. 14). The lake is bordered on the north by a moraine which is 4-5 meters high. On the eastern end, it is bordered by sand and rocks where the river branches out into the lake. In the south, there is a delta-like beach probably produced by the small streams there. The bottom is very flat out to about 75 meters and consists of fine sediment material, often beautifully formed by ripples. Towards the west, down towards the valley, moraines, rocks and blocks, and bedrock are found. The outlet consists of a short river reach in a fault in the bedrock terminating in a vertical water fall. With a measuring tape and a theodolite, a work map to the scale 1:1,000 was constructed for the surface area of the lake at reference level 162 cm during the summer of 1968. The observation period was from June 12 to August 29.

#### Sediment Studies in 1969

The discharge was measured at point A (Fig. 15) by readings on a fixed staff gauge, and at point C stages were recorded by a stage recorder. The discharge at point B is calculated from the stage recorder readings at point C and a knowledge of the size of the lake. This calculation was performed in the same manner as at Nigardsvatn. It should be noted that this method is not quite satisfactory for Vesledalsvatn, as the surface area of the lake is too small, and this implies that the influence of west and south streams will be too great.

It is probable that for Vesledalsvatn it would have been better to use the discharge values at the outlet (point C) and let these values also apply to the inlet (point B), possibly with a few corrections. A closer investigation of the smaller streams' influence on the total discharge ought to be performed during 1970.

Sediment samples were taken at points A, B, and C. The test sites at

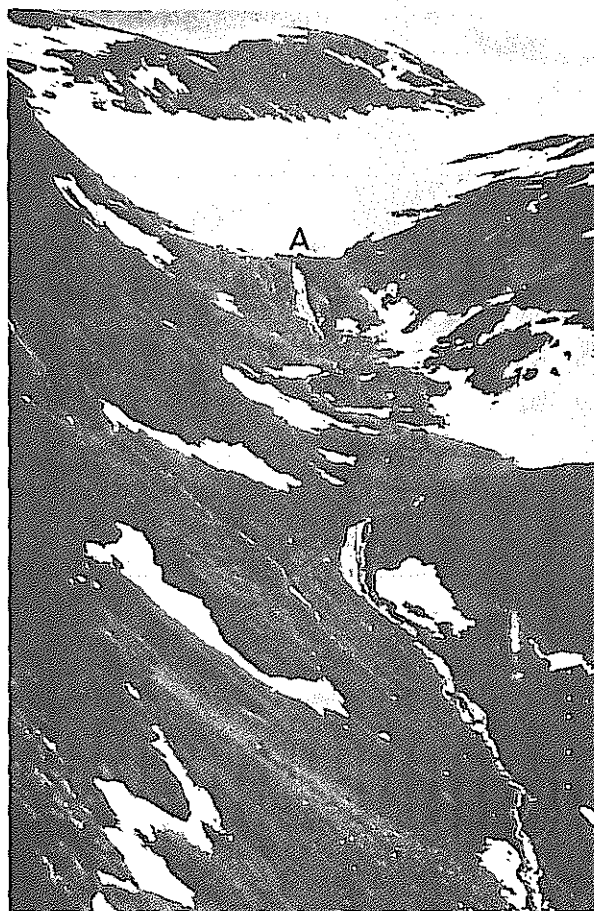
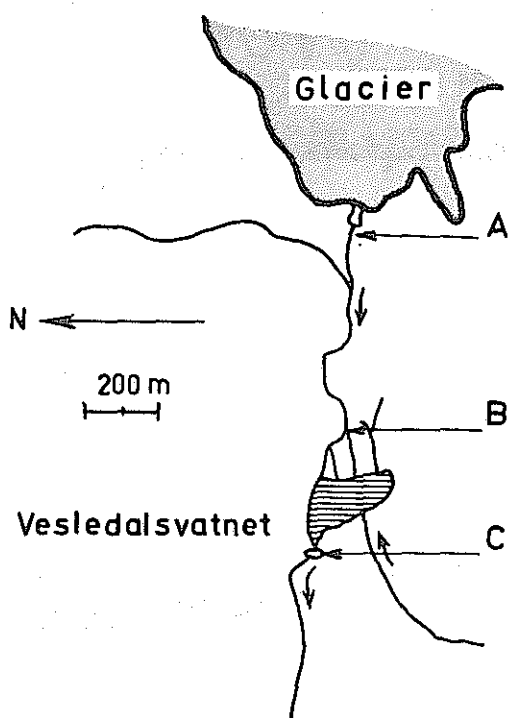


Fig. 15. Sketch and photograph showing Vesledalsbreen and the locations of silt sampling stations in the watercourse draining from the glacier.

A and B have turbulent water, whereas the river at point C has a less turbulent flow. The cross-section area at C is small, however, and the samples are therefore considered representative. The discharge and the sediment transport are calculated by data processing in the same way and with the same program as was used for Nigardsvatn.

During the field season, 579 metric tons of sediment material were estimated to have passed the test site at the glacier front (A), approximately 617 metric tons passed the inflow to Vesledalsvatn (B), while 382 metric tons passed the outlet (C). Between A and B, there is a net erosion.

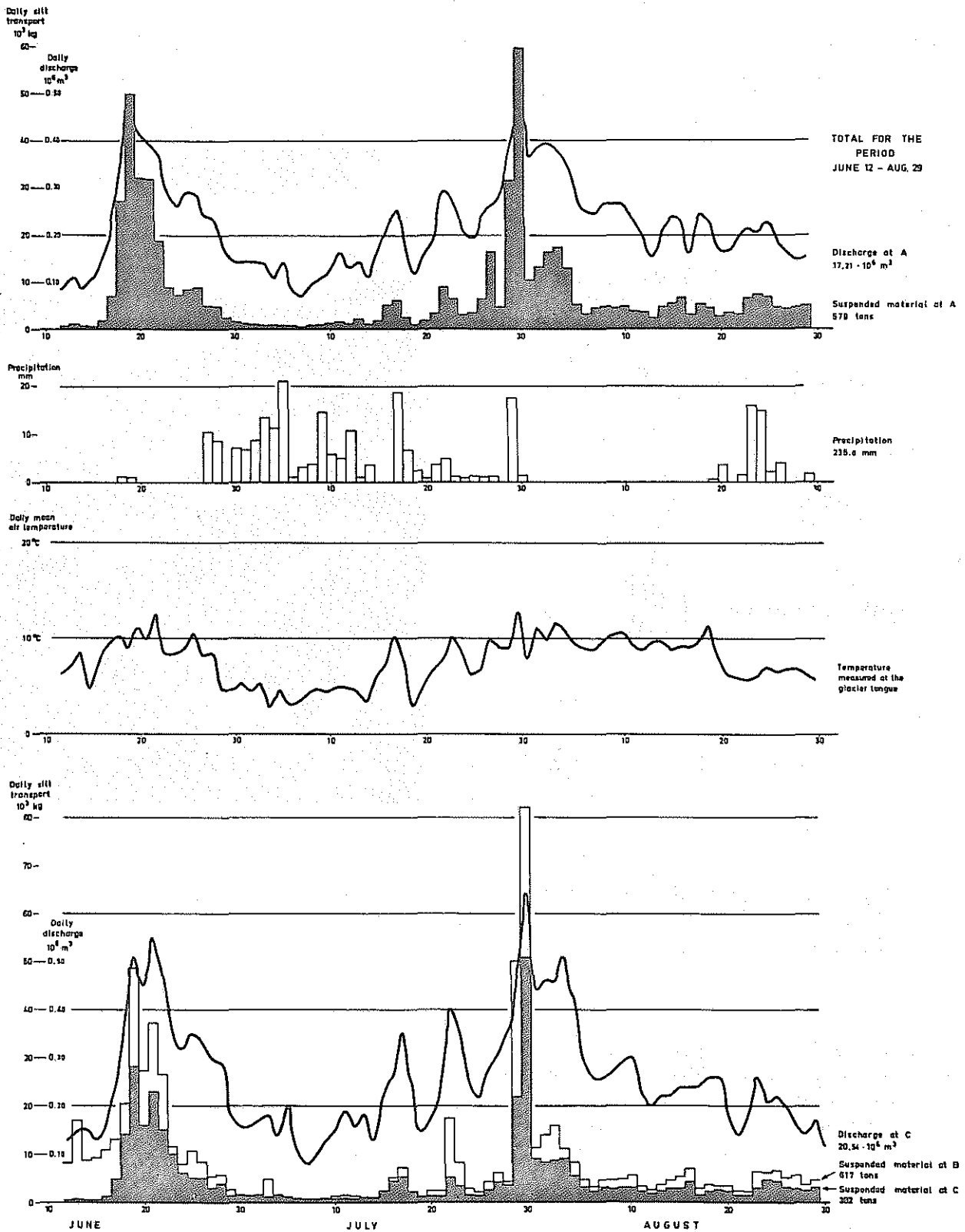


Fig. 16. Sediment transport and meteorological observations at Vesledalsbreen for 1969.



### Sedimentation Studies

The bed load transport has been investigated by a thorough sounding of the lake in 1968 and 1969. The soundings were performed in the same manner as in the inner part of Nigardsvatn, with wires across the lake at 5 profiles (Fig. 14). The soundings were performed from a boat at a total of 90 points.

Concerning the uncertainty of sounding values, the general discussion for Nigardsvatn may also be said to apply to Vesledalsvatn. From the sounding profiles of 1968 in Fig. 14 it may be seen that the bottom is quite uneven, the steepest part towards the delta (profiles 4-3 and 6-5). Changes in the accumulated material probably take place through avalanches in the steep delta area at increasing water level. This may explain the formation shown at profiles 2-1 and 4-3. The high threshold at the outlet probably causes the coarse material transported into the lake to remain there.

Calculation of the accretion on the bottom of the lake has been performed manually through a division of the surface area into a number of areas. The mean value of the difference between the sounding within each surface area has been multiplied with the said area and for the mass calculation, the specific weight  $2000 \text{ kg/m}^3$  has not been used. To obtain an idea of the uncertainty in the final result, the size and the number of the areas have been varied. The results from four of these different calculations gave the following four volumes: 836, 783, 757 and  $803 \text{ m}^3$ .

### Summary

The data for sediment and precipitation are shown in Fig. 16 for the measuring points A, B, and C. The table in Fig. 17 gives similar values for eight 10-day periods, and these values show:

- a. During 4 periods, the sediment transport was larger at B than at A. This implies that an erosion of earlier deposited material along the river had taken place. During the other 4 periods, the sediment transport was larger at A, and this implies that material again was deposited along the river. The total result for the field season gives, however, a net erosion of approximately 38 metric tons of material along the river.
- b. The water discharge at C was naturally larger than at A because of precipitation in the area and because of additional discharge from small streams into the lake. The difference is  $3.33 \times 10^6 \text{ m}^3$ . The precipitation during the period was 235.0 mm which caused addition of water from the sides and this was approximately 11 per cent of the total discharge at C.

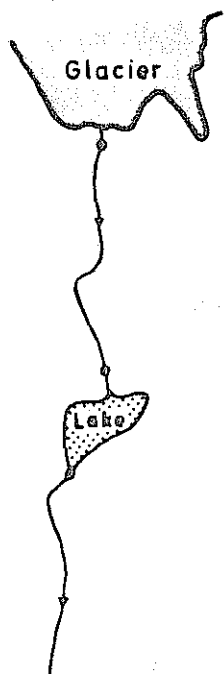
The accumulated material in the lake during the period August 30, 1968 to July 1, 1969 was  $759 \text{ m}^3$  or 1,590 metric tons, which implies a cross-sectional accumulation of 4.25 cm in the lake. This value seems much too high and must be considered suspect. The measurements for next

year may confirm this.

A synopsis of the above results is found in Fig. 17, where values for 1967 and 1968 are included (Tornås, 1968 and 1969).

### SEDIMENT TRANSPORT

| Period | Time        | at     |        |        | Accumulated along the river between A and B Tons | Water discharge $\times 10^6 m^3$ |       | Precipitation mm |
|--------|-------------|--------|--------|--------|--|-----------------------------------|-------|------------------|
|        |             | A Ton  | B Ton  | C Ton  |  | A                                 | C     |                  |
| I      | 12/6 - 21/6 | 153.11 | 153.07 | 91.08  | + 0.04   | 2.36                              | 2.83  | 2.0              |
| II     | 22/6 - 1/7  | 67.84  | 80.13  | 53.09  | -12.29   | 2.40                              | 2.94  | 25.9             |
| III    | 2/7 - 11/7  | 9.68   | 12.32  | 6.86   | - 2.64   | 1.18                              | 1.45  | 89.1             |
| IV     | 12/7 - 21/7 | 26.08  | 24.89  | 21.88  | + 1.19   | 1.65                              | 2.11  | 45.6             |
| V      | 22/7 - 31/7 | 148.98 | 188.14 | 104.33 | -39.16   | 2.91                              | 3.70  | 29.6             |
| VI     | 1/8 - 10/8  | 85.64  | 76.30  | 50.00  | + 9.34   | 3.04                              | 3.53  | 0                |
| VII    | 11/8 - 20/8 | 42.16  | 39.81  | 26.44  | + 2.35   | 2.05                              | 2.30  | 3.4              |
| VIII   | 21/8 - 29/8 | 45.19  | 42.40  | 28.32  | + 2.79   | 1.62                              | 1.68  | 39.4             |
| TOTAL  |             | 578.68 | 617.06 | 382.00 | -38.38   | 17.21                             | 20.54 | 235.0            |



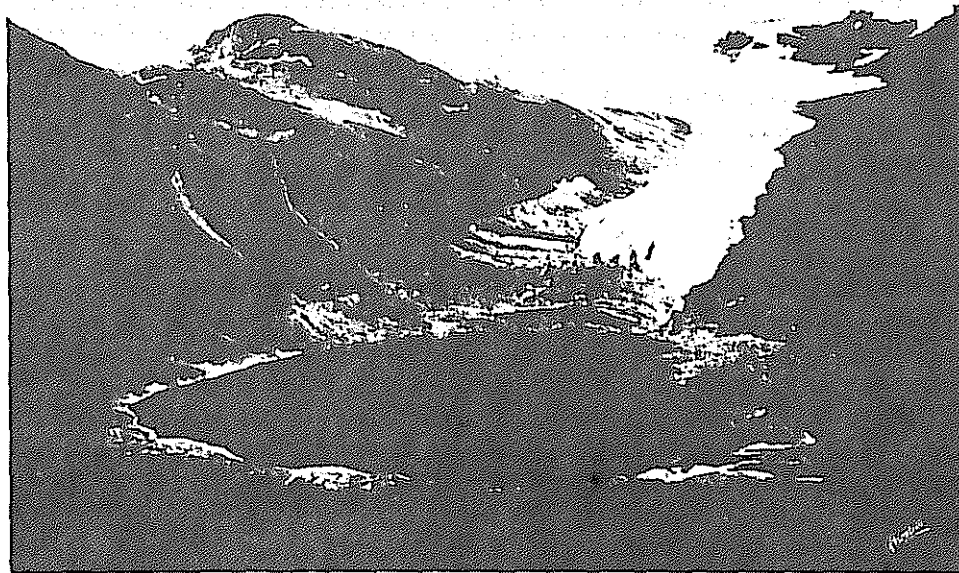
|                              | 1967              | 1968 | 1969      |
|------------------------------|-------------------|------|-----------|
| A                            |                   |      |           |
| Suspended material Discharge | 630               | 303  | 579 tons  |
| Accumulation along the river |                   | -191 | -38 tons  |
| B                            |                   |      |           |
| Suspended material           |                   | 494  | 617 tons  |
| Accumulation in lake:        |                   |      |           |
| Suspended material           | 140               | 103  | 235 tons  |
| Bed load                     |                   |      | 1590 tons |
| C                            |                   |      |           |
| Suspended material Discharge | $11.0 \cdot 10^6$ | 391  | 382 tons  |
| Precipitation                |                   |      | 235 mm    |

Fig. 17. Synopsis of observations for 1967, 1968, and 1969 from Vesledalsbreen.

### Engabreen

The Norwegian Water Resources and Electricity Board started hydrological and glaciological investigations in the Svartisen area in 1969. As a part of this work, observations were performed on sediment transport and sedimentation in the waters leading from Engabreen during the summer of 1969.

Engabreen is a west tending arm of the Svartisen glacier. The surface area of the glacier is approximately 39 km<sup>2</sup>, and the length is approximately 12 km. The highest point, near Snetind, is approximately 1,600 meters above sea level and more than 70 per cent of the glacier is on a large plateau 1,100 meters above sea level. From 1,100 meters, the glacier falls to about 500 meters above sea level over a distance of over 2 km. The present glacier front, 1.5 km further down, is situated at approximately 80 meters above sea level.



*Fig. 18. Photograph of Engabreen with the lake in the foreground. The sides of the valley to the lake exhibit an easily distinguished vegetation boundary indicating the extent of a former glacier stage.*

Engabreen is a very clean glacier. There is hardly any loose stone material on the surface.

Studies of the movements of the glacier which were conducted on the glacier arm during the summers of 1950 and 1951 show that the velocity of the glacier varied from place to place. The measured velocity was from 30 cm to 1 m per day (Bergersen, 1953).

In the course of the present century, the glacier has retreated considerably. In 1891, the distance from the end of the Holandsfjord to the glacier front was about 1 km (Rekstad, 1912). From then and until the last part of the 1920's, the glacier front has moved short distances back and forth (Holtedah1, 1960). Since 1930, the retreat has been rapid, and only during the last three years has there been a short move forward to its present position, 2.5 km from the fjord. In the area which previously was covered by the glacier, there is now a lake with a surface area of 1.2 km<sup>2</sup> at 10 m above sea level. The length of the lake is 1.8 km and greatest measured depth is 90 m. The volume is presumed to be approximately 40 million m<sup>3</sup>.

From the glacial front about 300 m above the lake, there is one larger river to the west and one smaller river to the east draining along two bedrock ravines down to Engabrevatnet and farther down to the Holandsfjord.

The rock bottom in the Engabre area is dominated by granite intrusions. Locally, the Caledonian foldings go east-west, with the axis towards the west. The upper parts of the glacier lie on the base of granite or rock of granodioritic character, while the glacial arm is on metamorphic sediments, which in the Holadsfjord area consist of mica shale quartzite, graphite and calcareous deposits.

#### Earlier Investigations

Just after the turn of the century, Rekstad (1912) calculated the eroding velocity of Engabreen based on the resedimentation of a small lake close to the then glacial front. The depth of the lake along the front was measured in 1891 to 30 m, and the greatest depth in the lake was 40 m. The surface area of the lake was approximately 70,000 m<sup>2</sup>. Rekstad suggested a water volume somewhere above 1 million m<sup>3</sup> and estimated the area of the glacier was 36 km<sup>2</sup>.

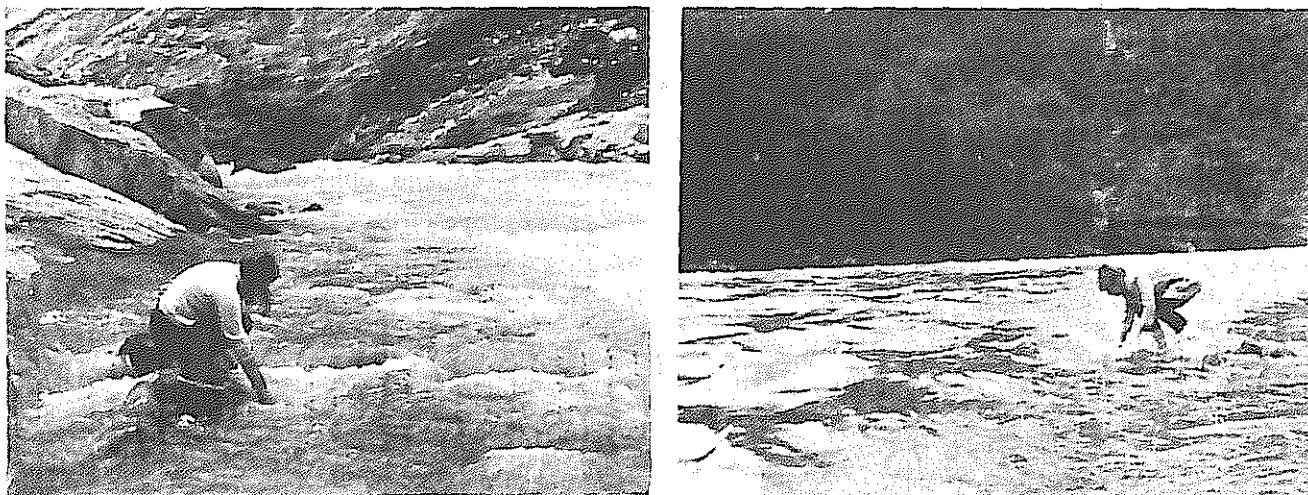
Until 1904, the lake was unchanged. Then the glacier moved in the same year, and the river bed was altered. In the course of the next 5 years, the lake was completely filled by sediment material and rocks. Based on the volume of fill and an evaluation of the quantity of material transported to Holandsfjord, Rekstad calculated that Engabreen erodes about 400,000 m<sup>3</sup> of material per year. This, according to Rekstad, implies an erosion of 11 mm per year if the erosion is evenly distributed over the glacier base.

Deposits and sediment production at Engabreen have also been described by Richter (1936) and Lundquist (1937).

#### The Investigations in 1969

Sediment transport and sedimentation studies under the management of the Institute of Water Resources were started June 23 and concluded August 18, 1969. A staff gauge was installed in Engabre Lake and sediment samples were taken at the main river inflow (to the west) into the lake and at the outlet from the lake (Fig. 19). The current at the test site

is clearly turbulent, whereas it is less turbulent at the outlet.



*Fig. 19. The sediment sampling sites at Engabrevatn. The entrance to the lake is to the left, the outlet to the right.*

The method of sampling is described by Ekman on page 9 (of this report; ed.). As may be seen from the discussion by Ekman, the accuracy of the methods is somewhat uncertain. The sampling at the inlet is, however, quite satisfactory for a description of the sediment transport by the test site. The samples taken at the main inflow to the west are adjusted to also include estimated sediment transport in the smaller flow to the east. Many more samples were taken at the outlet of the Engabrevatn than at the inlet, and it is therefore a possibility that the description of the sediment transport at the outlet is not quite satisfactory.

The conditions for sediment sampling and sedimentation studies at Nigardsvatn and Engabrevatn are practically the same. The data processing program for Nigardsvatn was, therefore, also used for calculations of sediment discharge and sedimentation in Engabrevatn during the observation period. A description of this program is found on page 16 (of this report; ed.).

The program comprises a correction for additional runoff from the catchment area of the lake which is not covered by the glacier. This catchment area is approximately 7 km<sup>2</sup> for Engabrevatn. Unfortunately, there were no precipitation readings at Engabrevatn until July 14. Corrections for precipitation on this area are therefore not included until this date.

### Results

Data from the observations and calculations of the summer are shown

in the diagrams in Fig. 20. The horizontal axes of the diagrams are identical, and the different data and calculations are therefore easily compared. Meteorological observations are shown in the other two diagrams. The observations of these parameters were only started during the week between the 14th and the 21st of July. Precipitation in the period prior to these observations is plotted on the basis of notations during times of sampling. To supplement the temperature observations, the mean temperature of the day from the Norwegian Meteorological Institute's climatic station in Glomfjord is plotted on the diagram with a broken line. This curve varies approximately with the observed temperatures at Engabreen.

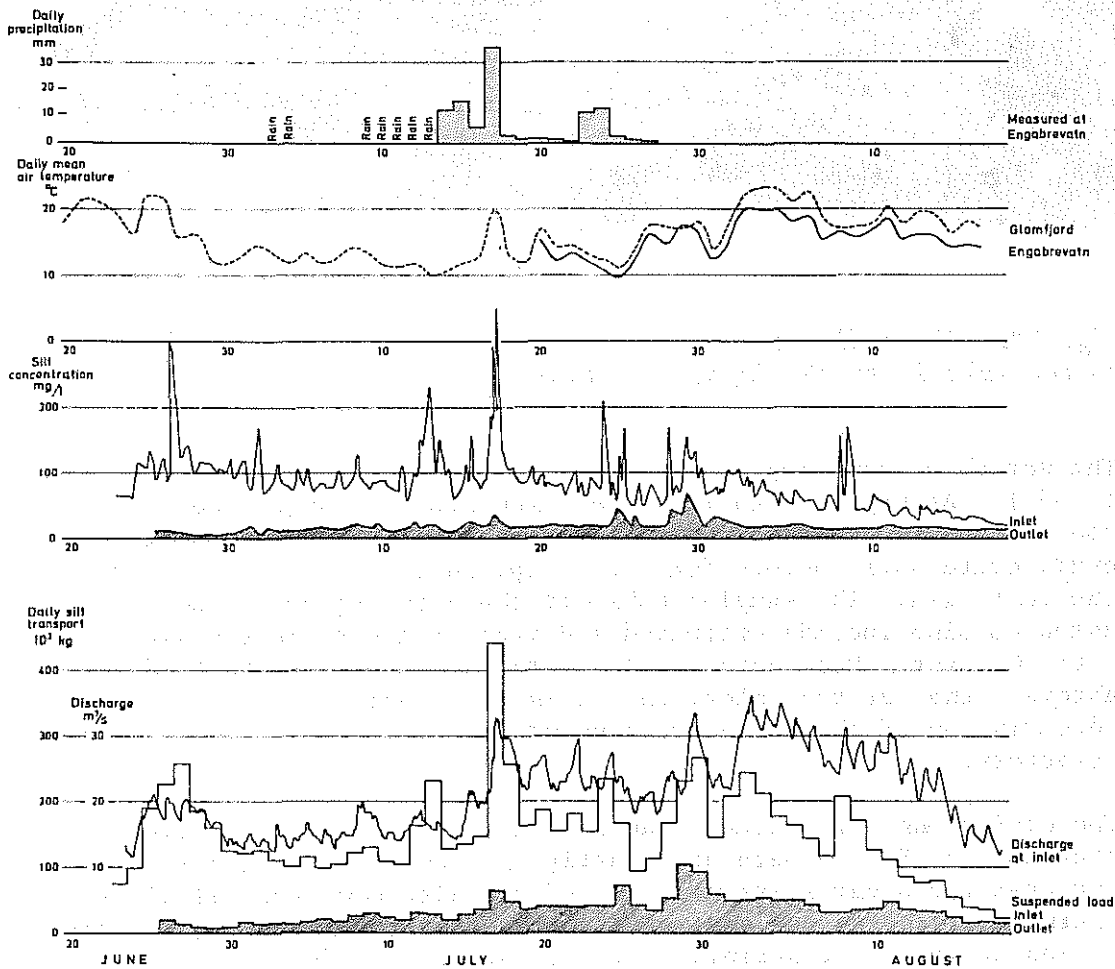


Fig. 20. Sediment transport and meteorological observations at Engabreen in 1969.

In the middle diagram, the observed sediment concentrations at the inlet and the outlet are plotted and two curves are drawn through the points. In the bottom diagram, the calculated discharge of the inlet into the lake is plotted in the form of a continuous curve along with a diagram for the calculated daily sediment transport at inlet and outlet.

The discharge roughly follows the variations in temperatures and is explained mainly by temperature through the influence of heat and the ablation of the glacier. The largest daily discharge, 2.84 million  $m^3$  on August 4, occurred in a period of high mean temperatures, while the lowest daily discharge, 1.19 million  $m^3$  on July 2, occurred in a period of relatively low temperatures.

The variations in sediment concentrations at the inlet to Engabrevatn are large. The highest concentration, 350 mg/l, was measured on July 17 while the lowest concentration, 20 mg/l, was measured on August 18. The sediment concentrations roughly follow the discharge within the same day. During the observation period, there was a downward trend in the average sediment concentration. The highest concentrations and transport quantities are associated with record high discharges at the beginning of the observation period. Similar discharges later in the period did not cause the same high concentrations and transport quantities.

It may be assumed that sediment material produced by the glacier in the course of a year is accumulated in certain areas below the glacier to be transported further during a short summer season. The volume of material available for transport is therefore probably largest in the beginning of the season, and this explains the unusually high concentrations coinciding with the early high discharges. When accumulated material in the most easily accessible areas has been washed away, increasingly higher discharges are necessary to reach new areas. In the course of the ablation season, it is possible that drainage of the glacier is also changed through the opening of new drainage channels (or old ones are reopened) so that new areas are washed over, adding to the amount of sediment for transport.

The variations of measured sediment concentrations at the outlet of Engabrevatn are small compared to the measured variations at the inflow. The highest concentration, 70 mg/l, was measured on July 29, while the lowest concentration, 4.22 mg/l, was measured on June 28. The curve of sediment concentration and the calculated daily transport are based on two and a maximum of three observations a day, and only at rare occasions are the samples taken during the highest discharge during the day. The lack of samples causes the calculated values for the outlet to be of some uncertainty. The sediment concentrations at the outlet have probably, on some days, been somewhat higher than indicated by the curve. The sediment transport out of the lake may possibly therefore have been higher than noted. The curves and the diagrams demonstrate, however, that Engabrevatn is an efficient sedimentation basin. Experiences from Nigardsvatn, where the conditions were similar, leave no further doubt that the large concentration variations at the inlet are strongly damped through the sedimentation which takes place between the inlet and the outlet.

A choice was made to base the calculations on the observed values for sediment transport at the outlet in order to estimate the sedimentation in Engabrevatn. It is, therefore, possible that the calculated values for sedimentation, in the observation period, are higher than the actual quantities.

For the observation period, it is calculated that 8,650 metric tons of sediment material were transported into the lake, while 2,000 metric tons were transported further out to Holandsfjord. These calculations were based on the sediment samples. This means that 6,650 metric tons or 77 per cent of the sediment material were deposited. For the same period it is calculated that 103 million  $m^3$  water was discharged through Engabrevatn.

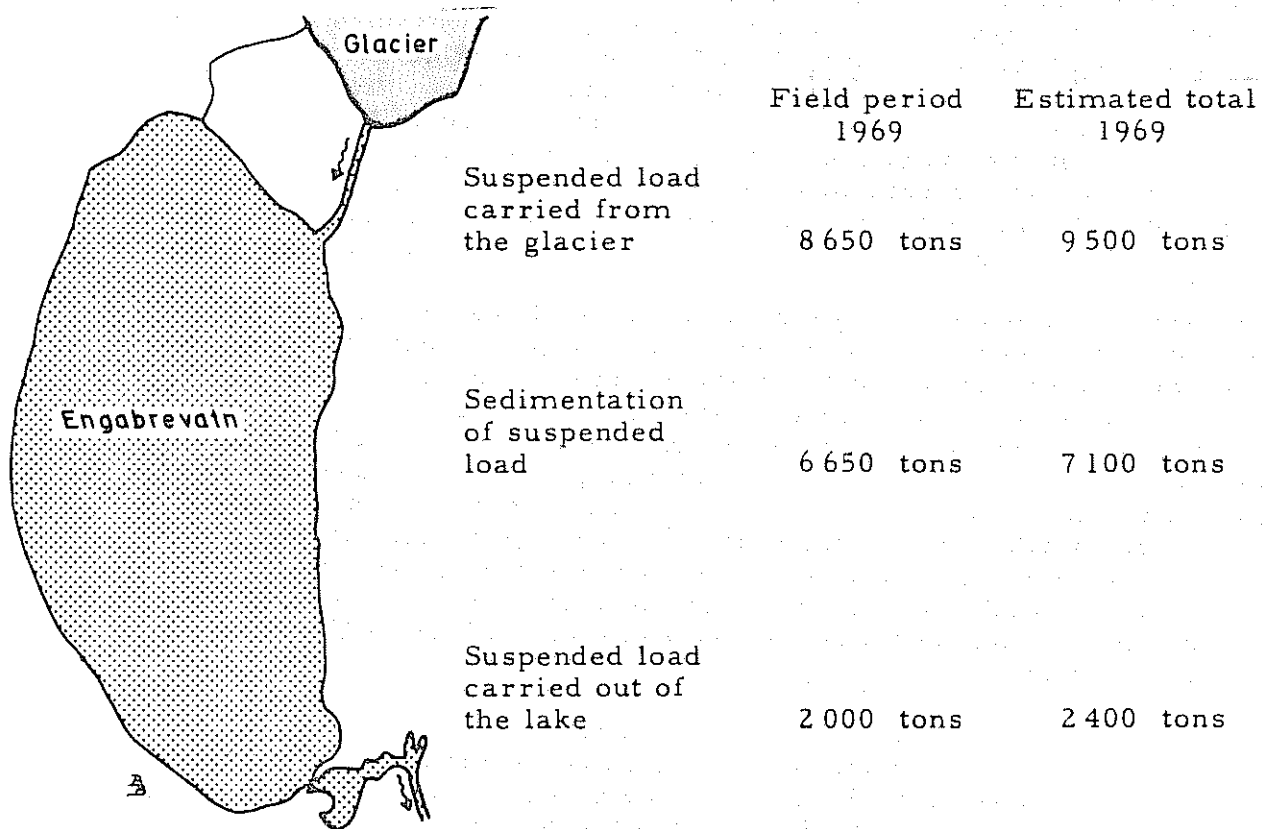


Fig. 21. Synopsis of the results from Engabreen in 1969.

The sediment transport processes were well underway at Engabreen in 1969 before the first observations were carried out. Sediment transport also continued for some time after the final samplings. Unfortunately, there are no records of observations which might aid an evaluation of these early and late sediment transport periods. According to Dyrkorn, a state hydrologist who visited the glacier several times before and after the observation period, the glacial river carried sediment material in measureable quantities between the 10th and 15th of June, and the transport continued until the beginning of October. He estimates the discharge around June 10 to be about  $5 m^3/sec$  on the average through the day, and at the end of September to be  $1 m^3/sec$ . Assuming the average discharge was increasing evenly up to the observation period and decreased evenly after the same, and at the same time an even increase in the mean sediment concentration from the beginning of June and an even decrease towards the end of September, it has been calculated that the



sediment transport into Engabrevatn was approximately 9,000 metric tons. An estimated 7,100 metric tons or about 75 per cent of this had been deposited in the lake in the course of 1969.

No measurements of the bed load transport in the streams from Engabreen have been undertaken. Based on the experiences with the net project at Nigardsbreen, where the conditions are comparable to those at Engabreen, one may assume that the amount of bed load transport is about 30 percent of the total sediment transport. If one assumed this to be equal to one year's erosion, the Engabreen's total production of material through erosion would be approximately 12,500 metric tons in 1969. This means a 0.16 mm abrasion under Engabreen if one assumes the erosion is evenly distributed over the ground below the glacier. This figure does not at all coincide with Rekstad's calculations of 1912 (he found 11 mm per year!) but corresponds more with similar figures for other glaciers where the Institute of Water Resources is carrying out investigations.

SEDIMENT TRANSPORT STUDIES AT ERDALSBREEN  
AND AUSTRE MEMURUBRE

Erdalsbreen

Observations of the sediment transport in the glacial river from Erdalsbreen were continued in 1961. The earlier investigations are described by Tornås (1967 and 1968).

Erdalsbreen is an arm to the west from Jostedalbreen and a neighboring glacier to the south of Vesledalsbreen (see Ekman, p. 29). Similar to the other glaciers that have been described, Erdalsbreen has been exposed to a strong melting process and retreat in the 20th century. Its present surface area is 11.2 km<sup>2</sup> and the length is 6.5 km. Its highest point is on Stornosi, about 1,800 m above sea level, and at the glacier front, it is about 860 m above sea level. Steep mountain walls surround the lower parts of the glacier, and ice is added through ice falls in many parts. Ice falls in the southern end are like avalanches. Large areas of the glacier may be considered steep. No movement studies have been performed at Erdalsbreen.



*Fig. 22. The upper part of Erdalsbreen. To the far right the southern icefall can be seen. Through avalanches this icefall supplies the glacier with large amounts of debris.*

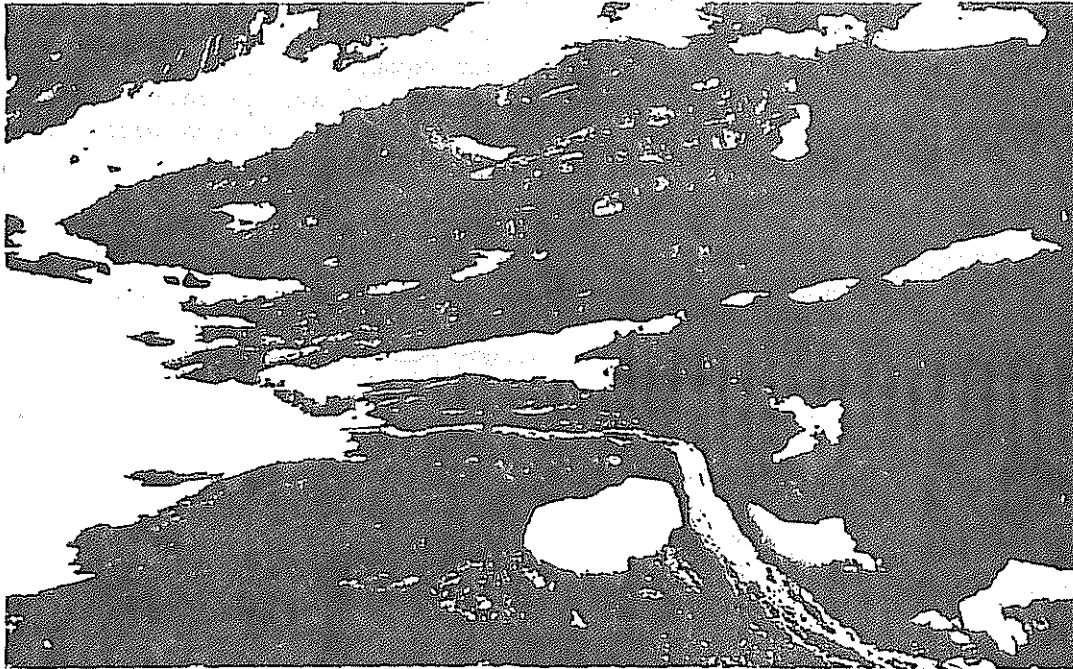
From the glacial front, two separated glacial rivers drain over bedrock and are combined approximately 40 m below. The river drains to Erdalen Valley where, in a large braided river area, it joins the river from Vesledalsbreen and then continues into Strynsvatn.

Erdalsbreen, like the rest of Jostedalbreen, is in an area where the

bedrock consists of gneiss, possibly metamorphosed earlier cambrosiluric shales and intrusions. The main streak of the caledonian folds in the area go east-west and the axes of the fold turn towards east.

#### The Investigations in 1969

The 1969 observations of sediment transport and discharge at Erdalsbreen were made during the period June 13 to August 29. The observation site is situated just below a point where two streams draining the glacier arm run together, and a staff gauge was erected there. The discharge was determined on the basis of regular, most often 4-5 daily readings, of the staff gauge. The catchment area above the gauge is 17 km<sup>2</sup>. The sampling methods were the same as for the previously described glaciers. The current at the sampling site was clearly turbulent.



*Fig. 23. The glacier front at Erdalsbreen with the site of the staff-gauge where water samples are collected indicated.*

#### Results

The observations and results for the summer are included in the diagrams in Fig. 24. The parallel time axis to the same scale makes the different diagrams easy to compare. The calculations are made on the new CDC 3200 computer at the Norwegian Water Resources and Electricity Board. The program is described by Ekman on page 16. The daily precipitation, measured in mm at the observation hut in front of Erdalsbreen, is shown in the top diagram. The curve below shows the daily

mean temperature as measured at the lower hut at Vesledalsbreen. Earlier investigations have shown that the daily mean temperature at the lower hut of Vesledalsbreen correlates well with the daily discharge at Erdalsbreen. (Østrem, 1969). One may observe that the discharge curve roughly follows the plotted daily mean temperatures. The discharge curve has, however, been somewhat modified for some periods due to the influence of the precipitation on the volume of discharge. In the period June 30 to July 4 it is estimated, based on precipitation observations, that about 1.2 million  $m^3$  (or about 30 percent) of the total discharge of 3.83 million  $m^3$  was contributed by precipitation on the tributary area.

The scale of the vertical axis of the sediment concentration diagram is greatly reduced compared to the similar diagram for Engabreen because of the very high concentrations measured at Erdalsbreen.

The highest sediment concentrations were measured at the start of the very high discharge at the beginning of the observation period. The highest sediment concentration of the season was measured June 21, when a water sample contained 3290 mg/l. For the five days from June 19 to 23, it is calculated that 3,500 metric tons of sediment material was transported past the observation site. This equals about 25 percent of the calculated total transport of sediment material in the period of observation. After the first flood, the sediment concentration decreased

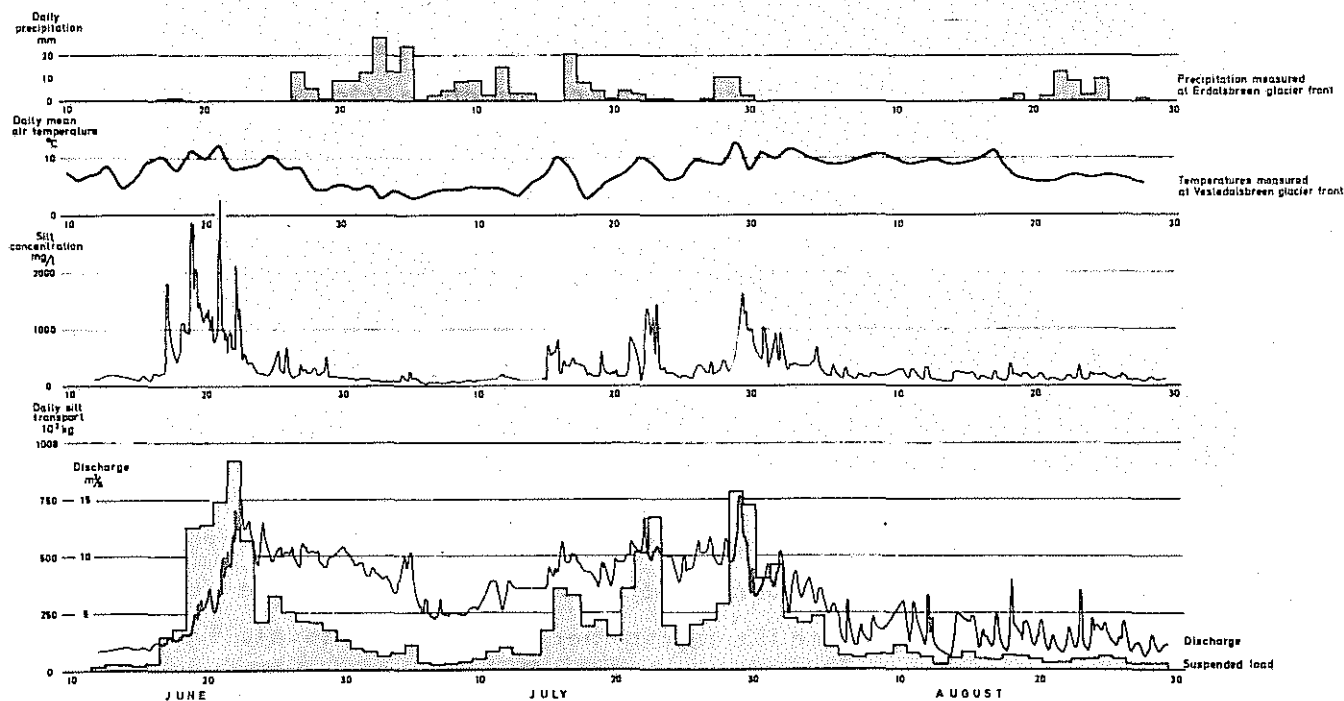


Fig. 24. Sediment transport and meteorological observations at Erdalsbreen in 1969.

and stayed low until July 15. The lowest concentration of the season, 15 mg/l, was measured on July 6. An increase in the sediment concentration and total transport occurred during the second half of July. Unfortunately, no observations were made between 0700 on July 28 and 2000 on July 29 when a large transport of sediment materials took place. The field observer was gone from the site during this period. The diagram shows that it is estimated that the same quantity of sediment material passed the site on July 29 as on June 22, when the highest measured daily transport took place. The sediment concentrations were low in August, and the discharge and the daily transport of sediment material were also relatively low until the end of the observation period.

It is estimated that during the observation period 14,729 metric tons of sediment material were transported by the observation site. At the same time, there was a discharge of 44 million m<sup>3</sup> from the same area.

As in the other observed glacial streams, the sediment concentrations and the daily total transport from Erdalsbreen depend on the amount of discharge due to ablation. As described for Engabreen, constantly higher discharges are necessary through the season to obtain similar high sediment concentrations later in a period as earlier in the same period. The flood at Erdalsbreen at the end of June shows this on a small scale. The highest sediment concentrations and the largest transport occurred at increasing water discharge, but before the discharge culminated. As the discharge reached new heights, the easily reachable areas of accumulated sediment material were washed over, and even greater discharges were necessary to wash over the previously flooded areas. The large daily transport in the second half of July was probably caused by fresh sediment quantities brought by the glacier to previously flooded areas, and drainage in the glacier through the ablation season possibly was changed so that sediment material from previously flooded areas was also transported away.

The sediment discharge in the glacial river before and after the observation period is unfortunately difficult to discuss. The closest parallel area where water level observations were made beyond the period is Vesledalsvatn. Usually the discharge changes here coincide with the observed discharges from Erdalsbreen. The first high discharge in Vesledalsvatn coincided with the earliest observed flood at Erdalsbreen. In all probability, therefore, there had been no larger water discharges from Erdalsbreen before this time. During the September - October period, the stage recorder at Vesledalsvatn shows 4 periods of high water discharge. These were mainly caused by precipitation. The conditions at Erdalsbreen were probably similar. The fraction of the discharge during this period caused by ablation is relatively small, and it is assumed that no extreme sediment transport had taken place. The total sediment transport from Erdalsbreen in 1969 is therefore estimated to be approximately 16,000 metric tons. If the experiences from Nigardsbreen are used as base for the calculations of the bed load transport, i.e. 30 percent of the volume of sediment transport, the total sediment transport of eroded material from Erdalsbreen will be about 21,000 metric tons. This equals an erosion of 0.95 mm under Erdalsbreen if the erosion is assumed to be evenly spread below the glacier.

### Austre Memurubre

The investigations of sediment transport by the river in front of Austre Memurubre were continued in 1969. Descriptions of earlier investigations were made by Tornås (1967 and 1968).



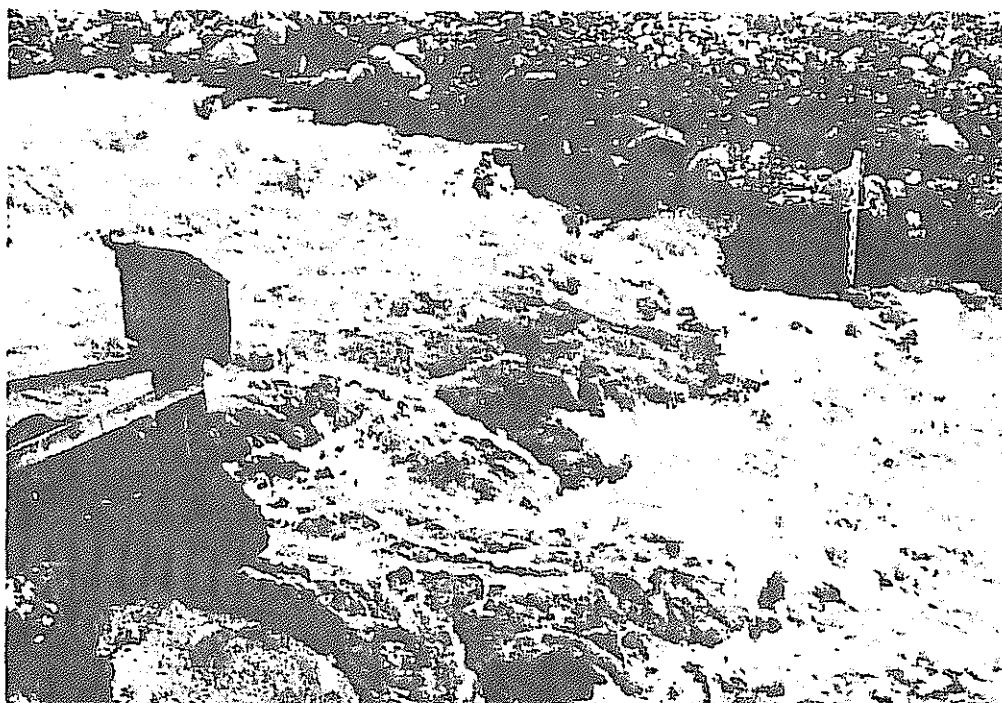
*Fig. 25. A central view of Austre Memurubre with the glacier front. In the foreground some of the numerous streams that drain from the glacier can be seen on their way through the loose deposits in front of the glacier.*

Austre Memurubre is a continental bottom glacier, in East Jotunheimen, with a surface area of 9 km<sup>2</sup> and greatest height of about 2,250 m above sea level. The lowest part of the glacier is at about 1,690 m above sea level. The glacier occupies one larger and one smaller valley, and the steepest parts of the glacier are found against the valley walls. Tall mountain tops surround Memurubreen. Movement studies were carried out by triangulation of a stake net, and surveys indicate that the glacier moves only very slowly. Observations made on June 15, 1968, and September 15, 1969, show that the largest movement of the stakes, 8 m, took place in the middle of the glacier, while movements of a little less than one m took place at the glacier front (Nielsen, 1970).

Between 1900 and 1952, it has been observed that the glacier front has receded by about 800 m (Liestøl, 1962). Since these front measurements were discontinued, the recession has continued. The lowest parts of the present glacier occupy a flat, broad valley bottom, and the area

that has been uncovered by the glacier retreat contains some moraine material. Through this area, some 8-10 larger and lesser streams are drained from the glacier front, and farther down the canyon, these streams combine into one main river. A gauging station has been erected on the river 1.5 km from the glacier front for sampling of sediment transport below the confluence of the small streams. Farther down the canyon, the river joins the stream from Vestre Memurubre which continues to Gjende.

The bedrock at Jotunheimen consists mainly of basic igneous intrusions often of a slatty or mylonitic character, and Austre Memurubre is situated within an area of so-called Jotun-norit.



*Fig. 26. The Memuru River at the water stage recorder. In a stream like this with a large bed load transport it is difficult to find a suited site for discharge observations.*

#### The Investigations in 1969

Observations were carried out from June 18 to September 1, 1969 of sediment transport in the streams fed by the glacier. At the gauging station, a staff gauge was erected, and a stage recorder was placed on the other side of the river (Fig. 26). The catchment area above the water stage recorder is 16 km<sup>2</sup>. The sediment samples were taken in 1 liter plastic bottles in the turbulent stream just below the water stage recorder.

During the observation period, samples were taken 3-5 times per day

at normal water discharge. During higher discharges, samples were taken every hour. Simultaneously, water level recordings were made. A couple of times during the period, technical errors prohibited the use of the stage recorder. Near the end of July and the beginning of August, a change was noted in the river profile at the water level recorder.

### Results

The results of the observations during the summer may be seen in the diagrams shown in Fig. 27. The horizontal axes are time axes with the same scale so that the different curves may be easily compared. The calculations were processed on the computer at the Institute of Water Resources. The top diagram shows the daily precipitation measured in mm at the lower observation hut at Memurubreen. Often the daily precipitation occurred as heavy showers over a few hours.

The diagram below shows the mean daily temperature at the lower hut. At the bottom of the diagram, water discharge has been plotted in the form of a curve along with the daily total sediment transport. The discharge follows roughly the variations in the curve for the mean daily temperatures. Sometimes, heavy showers would lead to an increase of the discharge. As an example, heavy showers over a couple of hours on July 17 led to the highest discharge during the observation period. The dis-

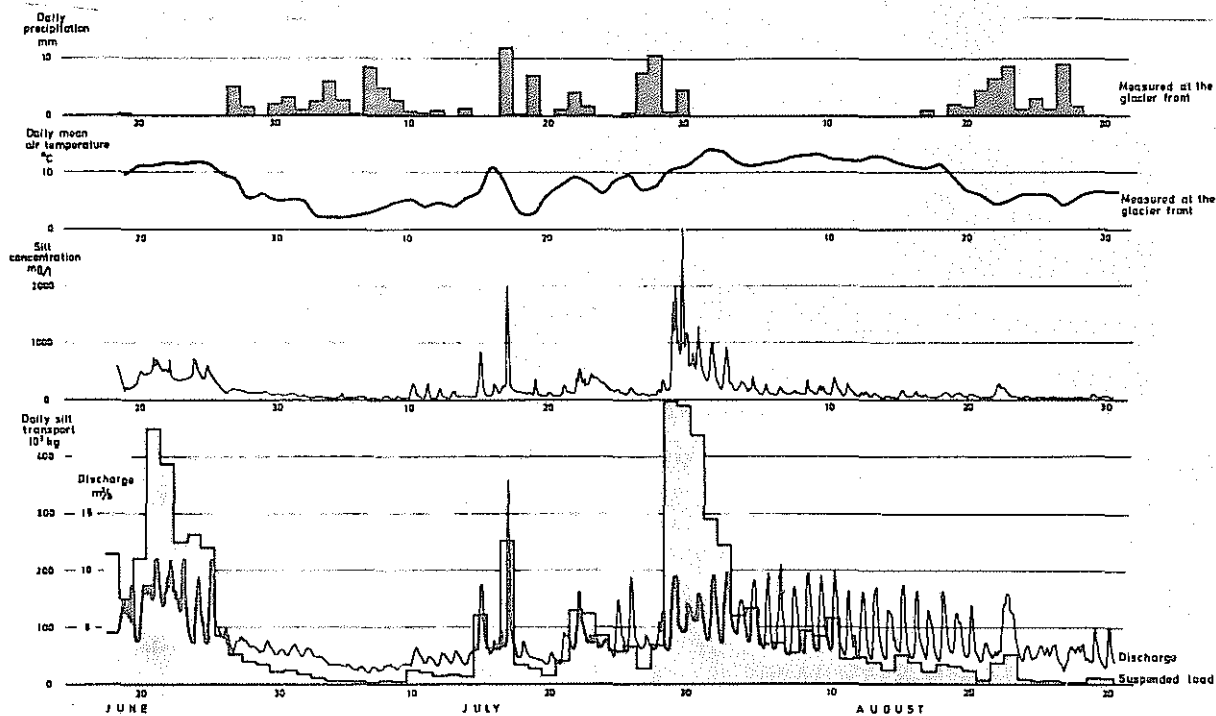


Fig. 27. Sediment transport and meteorological observations at Austre Memurubre in 1969.



charge resulting from these showers is calculated to be about 0.19 million m<sup>3</sup> for the total catchment area above the observation station. A large part of the total measured discharge was, therefore, caused by the showers. The scale for the sediment concentration curve is, as for Erdalsbreen, reduced 10 times along the vertical axis, compared to the similar diagram for Erdalsbreen, because of the unusually high sediment concentrations that occurred during the summer, especially near the end of July and beginning of August. The highest sediment concentration of the observation period, 3,037 mg/l, was measured on July 30, while the lowest concentration, 11 mg/l, was measured August 25. The first high sediment concentrations and large daily transports for the observation period are associated with high daily mean temperatures, glacier ablation, and discharge from the glacier between June 17 and 27. The large transport during this period was mainly caused by erosion of sediment by the glacier.

An unusually high sediment concentration and discharge peak on June 17 was a result of the very heavy precipitation on that day as described above, and it is possible that the resulting heavy discharge in the area around and especially in front of the glacier caused erosion of the moraine material. The high sediment concentration on this date is, therefore, probably mainly caused by erosion of loose materials in front of the glacier.

The highest sediment transport of the season occurred on July 29. It is calculated that approximately 500 metric tons of sediment material were carried past the gauging station in the course of this day. The following next four days were also marked by large transports, and within this period a change in the profile at the water stage recorder occurred. In the beginning of the period, the daily mean temperature increased measurably during fair weather until about August 20, and this caused high daily discharges. The highest calculated total transport did not coincide with any real record discharge. Usually the highest concentrations and transport of sediment materials coincide with the first high water discharges in the ablation season. In order to obtain a total transport of sediment materials from the glacier of similar quantities later in the season, usually much higher water discharges than these first must occur. In the period July 29 to August 3, the discharges were smaller than the earlier high discharges between July 19 and 26 when large quantities of sediment material accumulated under the glacier were washed away. The change in the profile at the gauging station occurred, however, near the end of July and the beginning of August due to erosion in the river bed. It may, therefore, be assumed that a large part of the transported sediment quantities between July 29 and August 3 were caused by heavy erosion of the river bed from Memurubreen, rather than by movement of accumulated sediment under the glacier.

It is therefore obvious that the sediment material which is transported past the gauging station in front of Austre Memurubre consists of material washed from under the glacier as well as sediment material eroded in the catchment area just above the observation site.

It has been calculated that 6,880 metric tons of sediment material

were transported past the gauging station during the observation period of 1969. During the same period, the discharge was calculated to be about 26 million  $m^3$ . This last figure compares well with the ablation figure for Austre Memurubre in 1969, about 21 million  $m^3$ , (Pytte, 1970), if it is taken into account that the water stage recorder also registers discharge from a large glacier-free precipitation area.

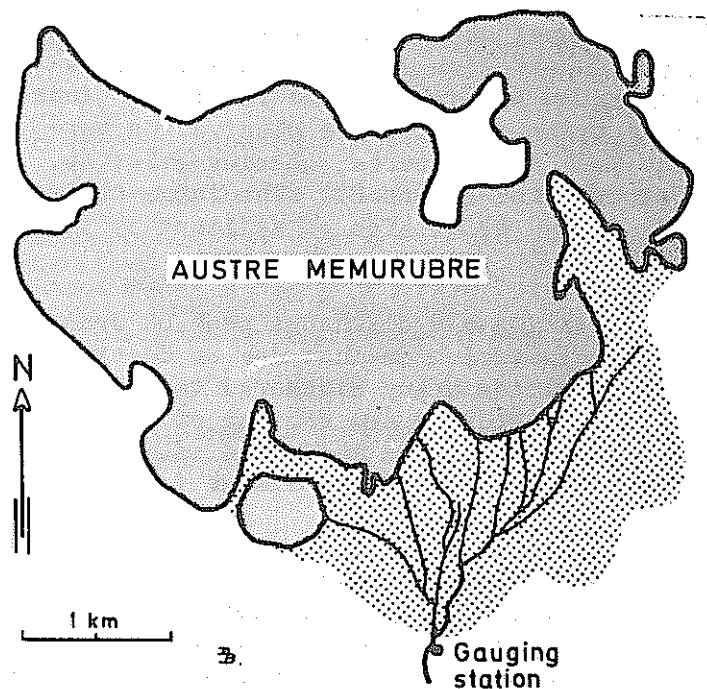


Fig. 28. Map and photograph showing Austre Memurubre and the area of loose deposits below the glacier front.

The map sketch shows Austre Memurubre and the small rivers draining from the glacier, with the river gauging station plotted. The darker area in front of the glacier shows the extent of the easily erodable loose deposits above the sampling station described in the text. These deposits consist of unsorted material free of vegetation and of considerable thickness. The photo below was taken in the area of deposits.



#### An Evaluation of the Glacial Erosion

Because the streams from the glacial front drain from an area of loose materials and because of the great distance from the glacial front to the gauging station, it is difficult to make a reliable calculation of the transport from the glacier. In the area between the glacier and the gauging station, it is estimated that in some periods sedimentation of glacier eroded sediment material will take place. At other times, erosion of the same river beds will occur. And finally, there will, at

times, be an erosion of other loose materials in front of the glacier. The sediment transport observed at the gauging station will therefore only equal the erosion of material from under the glacier during some periods. An evaluation of the sediment production at Memurubreen based on observations at the gauging station below the confluency of all the streams from the glacier front must therefore be based on more or less qualified suppositions.

The calculated total transport of sediment material past the gauging station during the observation period was 6,880 metric tons. Some of this was from erosion in the river beds and the loose materials in front of the glacier, and even if at other times there was a deposition of material between the glacier and the gauging station, one may with some certainty assume that the erosion was appreciably larger than the deposition. The sediment volume from the glacier alone during the observation period was therefore assumed to be approximately 4,500 metric tons. The observation period probably covered the time span when the largest sediment transport from Memurubreen took place. The ablation season of the glacier lasted only shortly before and shortly after the sediment studies were started and discontinued. It is therefore assumed that about 9/10 of the total transport in 1969 occurred within the observation period. The total sediment transport from the glacier in 1969 will therefore be approximately 5,000 metric tons. Finally, there was, in addition, a production and a transport of coarser material than suspended sediment. Austre Memurubre may hardly be compared to Nigardsbreen to the same degree as Engabreen. Still, it is appropriate to assume that the quality of coarser fractions produced by erosion equals about 30 percent of the sediment volume. Based on the above presumptions, it is calculated that the volume of material transported from under the glacier in 1969 equals about 6,500 metric tons. If the specific weight of the rock is assumed to be 2.8 and if it is assumed that the said volume was evenly spread under the whole glacier, this equals an erosion of 0.26 mm.

## CONCLUSIONS

The results from sediment observations in 1969 are compared to previous years' results in Fig. 29. In addition to the results for Engabreen, Endalsbreen, and Austre Memurubre, similar data for Nigardsbreen and Vesledalsbreen are included based on the 1969 calculations by Ekman.

The number of weeks of observation in the course of each year together with the calculated sediment transport within the observation period are included for each glacier. Further, on the basis of these calculated values, an evaluation of the total material transport from each glacier within the same year has been made. In the evaluation, the discharge from each glacier before and after the observation period has been taken into consideration, and the sediment transport outside of the observation period has been assumed on this basis. The bed load transport has been calculated to be 30 percent of the yearly volume of sediment transport, and together, these volumes will give the assumed yearly material transport from each glacier.

The assumed yearly transport is divided by the surface area of the glacier, and the abrasion is calculated assuming it to be uniform over the entire area covered by the glacier.

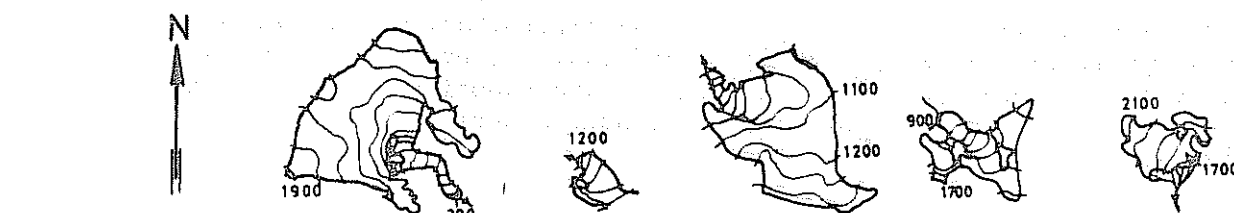
The figures in the table show large differences in amount of material transported past the gauging stations on the rivers from the different glaciers. In addition, there are variations in the transport from the same glacier from year to year.

A guide line for further studies of material transport will be to investigate the validity of the methods for sampling and calculation and to identify the factors which may help to explain the variations in the volume of material transport from place to place.

Ekman, on page 12, showed the necessity of making systematic tests and evaluations of the methods in order to determine the possible errors that may be included in the calculations due to the methods of sediment sampling. To say that the measuring method is representative is highly dependent on the conditions at each of the gauging sites, and especially on the turbulence in the river above the site. Investigations over the total river cross-section at each gauging site are, therefore, advisable. This is true also for the different discharge conditions in order to determine the variational distribution of the fine material in the river cross-section at all times. Other measuring methods ought to be attempted simultaneously - for example, a photometer which can register continually. Only through such investigations may knowledge be obtained of how and where observations should be performed and if the measurements are representative of the actual sediment transport.

The main annual material transport takes place within the observation periods. The volume of discharge from the glaciers is larger at the beginning of June and until some time in October. The volume of sediment transport in the rivers is especially high during the first high water discharges in the spring due to the ablation of the glaciers. The sedi-

## INVESTIGATIONS OF SEDIMENT YIELD AT SELECTED GLACIERS IN NORWAY



| Glacier name                      | Nigardsbreen                         | Vesledalsbreen | Engabreen | Erdalsbreen | Austre Memurubre |      |
|-----------------------------------|--------------------------------------|----------------|-----------|-------------|------------------|------|
| Area, km <sup>2</sup>             | 40                                   | 4              | 39        | 11          | 9                |      |
| Number of weeks with observations |                                      | 7              |           | 6           | 9                |      |
| 1967                              | Observed silt-transport, tons        |                | 530       |             | 7840             | 4700 |
|                                   | Estimated total annual transport     |                | 1000      |             | 15000            | 6000 |
|                                   | Sediment yield, tons/km <sup>2</sup> |                | 250       |             | 1360             | 630  |
|                                   | Corresponding erosion in mm          |                | 0.12      |             | 0.70             | 0.22 |
| 1968                              | Number of weeks with observations    | 12             | 11        |             | 10               | 11   |
|                                   | Observed silt-transport, tons        | 4370           | 300       |             | 6300             | 3300 |
|                                   | Estimated total annual transport     | 6000           | 500       |             | 10000            | 4500 |
|                                   | Sediment yield, tons/km <sup>2</sup> | 150            | 125       |             | 910              | 500  |
| Corresponding erosion in mm       | 0.07                                 | 0.06           |           | 0.45        | 0.18             |      |
| 1969                              | Number of weeks with observations    | 13             | 11        | 8           | 11               | 10   |
|                                   | Observed silt-transport, tons        | 13910          | 579       | 8650        | 14720            | 6880 |
|                                   | Estimated total annual transport     | 22000          | 900       | 12500       | 21000            | 6500 |
|                                   | Sediment yield, tons/km <sup>2</sup> | 550            | 225       | 320         | 1910             | 720  |
| Corresponding erosion in mm       | 0.27                                 | 0.11           | 0.16      | 0.95        | 0.26             |      |

Fig. 29. Synopsis of results from sediment transport studies for 1967, 1968, and 1969.

ment transport during the fall flood, which may not occur until some time in October and which is usually caused by precipitation, has not been investigated to any extent, as it is difficult to procure observers at that time. In order to gain knowledge of the quantity of sediment transport in the fall, one would like to extend the period of observation somewhat.

The net project at Nigardsbreen gave important information about the bed load transport in the glacier river, and it is obviously necessary to intensify the studies of bed load transport.

The relatively simple and quick method which was used to measure the accumulation in the delta at Nigardsvatn will also over a period of several years give good information about the volume of bed load transport at Nigardsbreen. At Engabreen and in front of several other glaciers, there are lakes close by the glacial front as at Nigardsbreen. By performing similar delta studies as those in Nigardsvatn, it is possible in a simple and quick way to extend the studies of bed load transport to also include several other glacial rivers and glaciers in different areas.

There are gauging stations close to the glacial fronts on the investigated glacial rivers except at Memurubreen. In addition, the glacier streams have a bedrock bottom and the main drainage from each glacier is contained in one main stream channel at the gauging stations. The data therefore directly measure the fine material, and only that, which comes from the glacier and which is eroded by the glacier. The investigations of sediment accumulation in the lakes make it, in addition, possible to measure the quantity of coarse material which is eroded by the glacier and later transported as bed load transport. These investigations make it quite possible to measure the volume of erosion by each glacier.

The differences and variations in the material transport reflected in the table shown in Fig. 29 are caused by individual differences between the glaciers and their erosion. To gain information about the causes for these variations and differences, the factors influencing the erosion of bedrock on the glacier bottom and the resulting transport must be investigated further.

The erosion by the glacier is mostly dependent on its base and the topography, the size of the glacier and its movement. In order to gain a better understanding of the eroding processes in each case, it is necessary to map the geology of the investigated glaciers in order to obtain an idea of the composition and character of the rock bottom below the glaciers. Parallel to making such a map, mineral investigations of the transported sediment might give interesting results. Further, it is of great importance to determine the volume of the glaciers, to map the topography below each glacier, and to extend investigations of glacier movements which are performed during the glaciological measurements on the glaciers.

The measured material transport does not, of course, directly reflect the erosion by the glaciers at all times. Some of the material that is measured has probably been eroded when the glaciers had a different vol-

ume but which only now is available for transport. This is the reason why it would also be of the greatest interest to find out how the eroded material is made available for further transport, first and foremost through air investigation of the drainage in glaciers.

The great differences in sediment transport from one year to the next make it necessary to continue the investigations over several years before it will be possible to determine the average and maximum quantities of sediment which may be expected to be transported from the glaciers at different times.

It must be stressed that it is of great importance that other parallel and thorough investigations are performed as those taking place at Norwegian glaciers through volumetric investigations and sediment production studies. This concentration of glaciological, hydrological, meteorological and erosion investigations, which are related to each other, makes it possible to gain knowledge of many of the glacier problems. A further concentration of glacial studies through additional investigations might lead to positive results.

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