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III

APPLICATION OF LANDSAT IMAGERY FOR SNOW MAPPING IN NORWAY

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Final Report

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GUNNAR ØSTREM

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15. Abstract		
Landsat-2 project No.29020 deals with snow cover mapping from satellite imagery to produce data for water resources management. The extent of snow cover within a given high mountain watershed as observed in the spring is directly related to the total volume of melt water run-off. Space-aquired data are valuable if they are received by the user within a few days, so that an operational use of the data can be possible. A simple, quick and easy-understood procedure is recommended:snow-covered areas are directly determined on photographic enlargements of Landsat images, preferably overlaid on a map of the catchment area. The area extent of snow cover is determined simply by counting squares or grid points. A diagram showing the relation between snow cover and subsequent melt water run-off has been established for several given catchment areas, but it seems that the same curve can be used also for other high-mountain drainage basins. The curve can be used directly for run-off forecasts as soon as snow-melt has startet. A special method has been developed for glacierized watersheds, based upon the height of the transient snowline.		

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PREFACE

One of the LANDSAT-1 experiments in Norway was concentrated on snow hydrology (Project No. F-418) with H. Ødegaard as the Principal Investigator. Another experiment was concentrated on glaciology and glacier hydrology (Project No. SR 376, "Evaluation of glacier mass balance by observing variations in transient snowline positions") with Dr. Gunnar Østrem as the Principal Investigator.

As a follow-on activity for LANDSAT-2, both these Principal Investigators prepared a proposal for continued observations of snow hydrology and run-off conditions. Such observations made via satellite data for large areas and checked by ground control in single points, may lead to a method that can be used operationally to predict available amounts of melt water at existing hydro-electric power plants in Norway. This is a vital concern for the management of Norwegian power stations, because all electricity produced in Norway is hydro-electric power. Most watersheds consist of high-mountain drainage basins which are snow covered all winter.

This proposal was accepted by NASA (Project No. 29020) and a great number of LANDSAT-2 images as well as digital tapes were received during the investigation period. The material made it possible for us to conduct a most interesting study of the relations between remaining snow on the ground (in the spring) and subsequent melt-water runoff. We are most indebted to NASA for giving us this opportunity to perform such studies.

This final report is submitted to NASA as a result of more than two years of investigations. Most of the work was done in high-mountain basins where images of the decreasing snow-covered areas proved to give valuable information for fairly reliable predictions of expected inflow to the water power reservoirs.

Glaciers play presently a minor role in the hydro-electric power system as only relatively small areas are glacierized. However, for certain power plants which are built (or planned) near large glacierized areas, a better understanding of the glacier hydrology is a vital concern. Therefore, special studies have been made also of glacier hydrology, based upon satellite data. Particularly the determination of the height of the transient snow line has proven useful in this connection because it is a direct measure of the glacier melt and, consequently, also a measure of expected waterflow from glacierized basins.

The present report has been prepared mainly by the principal investigator, Helge Ødegaard, whereas the co-investigator, Dr. Gunnar Østrem, has been dealing with the chapter on glacier hydrology and he took also care of several technical details in the preparation of the report, both the text and the presentation of results in diagrams etc.

One of the main results from this study is the curve, shown in Fig. 11, which is a kind of a "template" to be used to transform satellite data to runoff predictions, directly useful for the management of hydro-electric power stations. However, it must be emphasized that all basic information which was used to produce this curve was acquired from particular basins, and more work has still to be done before the curve can be used more generally, i.e. for other basins in Norway or elsewhere.

To make this report useful also for other individuals who may have similar problems, i.e. to evaluate the expected water runoff from a melting snow cover in order to produce a running, operational forecast, we have tried to explain our method in such a detail that the report may be used more or less as a handbook when the methods are implemented in other areas. The method will be useful in high-mountain watersheds where the melt water is utilized for hydro-electric power production or for irrigation.

The work was performed at the Norwegian Water Resources and Electricity Board - a Governmental body which is responsible for planning, construction, and running of all State-owned power plants in Norway. About 30 % of the total amount of electric energy produced in Norway is delivered from these State-owned hydro-electric power plants. It is, therefore, of greatest interest to the State Power Board (a division within the Norwegian Water Resources and Electricity Board) to try to implement all possible new techniques in the daily operation of these power plants.

During recent years various systems of data acquirement, data telemetering and data processing have been implemented to increase the efficiency and reliability of the electric power system in Norway. It is hoped that the use of satellite data will form a new and valuable tool to improve predictions of expected meltwater inflow into our reservoirs.

Oslo in September 1977

H. Ødegaard

G. Østrem

BACKGROUND FOR SNOW SURVEYS

The Norwegian Water Resources and Electricity Board (NVE) produces annually 23,000 GWh or 30 per cent of the electric energy in Norway and operates 45 hydro-electric power plants in the country. The rest of electric power is produced in hydro-electric power plants owned by communities or private companies. No electricity is produced by thermal or nuclear methods. Snow surveys in high-mountain catchment areas are therefore a vital concern for the management of power plants in Norway.

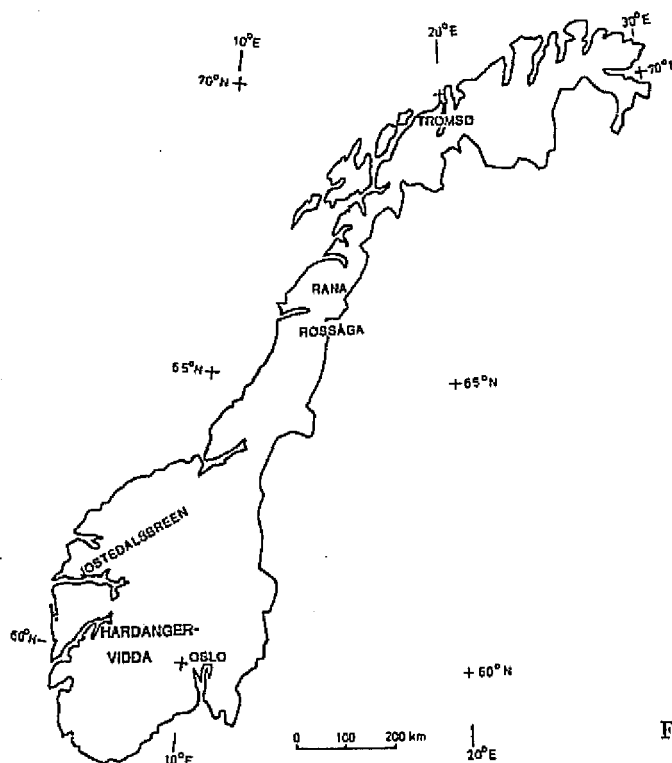


Fig. 1 Location map.

Snow sampling is made in selected points on a routine basis within all major catchment areas. A current project on natural gamma radiation is in operation. The method is based upon the reduction of the natural gamma radiation from the ground, recorded from low-flying aircrafts. The attenuation is directly related to the water content of the snow cover (and of soil moisture, but errors from water in the soil are kept small by a careful selection of measuring profiles).

The regular snow surveys are made in the first week of February and the first week of April, when the snow cover is thick. Other methods must be used in the spring to determine the areal extent of the melting snow. The winter production of power and the draw-down of the reservoirs start in November. When the result of the first snow survey is available at the beginning of February, the first corrections in the production plans are made, and decisions are made concerning how to distribute the total load between various power plants in different areas of the country,

relative to the size of their snow reservoir and ability to take care of the water during the following summer.

This means that a power plant with a large amount of snow in February will run on high load to make room in the reservoir for the expected large melt water volume. The plants with little snow will aim at a lower production in the months February through July. This "direction of production" takes place in a free market with buyers and sellers, and is made possible by a well developed network of power lines. When the result of the snow survey in April is available, new production plans are prepared and the load on the different power plants is reconsidered.

From the start of snowmelt (about May 5) until it ends (about August 1) very little information is available on conditions during the melting procedure. Some years a large amount of water may disappear due to evaporation or filling up the groundwater reservoir, other years the snow melts rapidly and, hence, only small losses due to evaporation are encountered. In this period precipitation is of course recorded and the data are used in the production plan.

However, the main problem is the fact that very little information is available on conditions within the snow-covered areas for three months.

The entire production system for electricity in Norway consist of hydro-electric power plants. Implementation of thermal or nuclear energy into the production system will increase prices on electric energy and make it necessary to improve the daily management of the entire system. Good snow measurements will play an important role in such improvements and contribute to increase the over-all efficiency.

Knowledge of the areal extent is particularly important in regions with seasonal snow cover, since it can change from 100 % coverage of a given basin down to zero within a relatively short time. It is obvious that the water production from a melting snow cover depends directly on its surface area. However, systematic measurements of seasonal changes of the snow cover have been limited until recently.

Methods for determining snow limits have so far been unsatisfactory. One of the main problems is the limitation of measurements to separate points only, or at the most, in small areas. Thus only a limited amount of data were available and it proved impossible to draw satisfactory maps of snow coverage.

The creation of satellite imagery made it possible to view a large area at the same time and with similar light conditions and with the possibility of spectral differentiation. This made it much easier to map the snow line, and consequently, a great interest has arisen among users to obtain such information.

The main task for our work has been to develop methods to determine the temporary snow limit as precise and quick as possible from satellite images and then to transfer

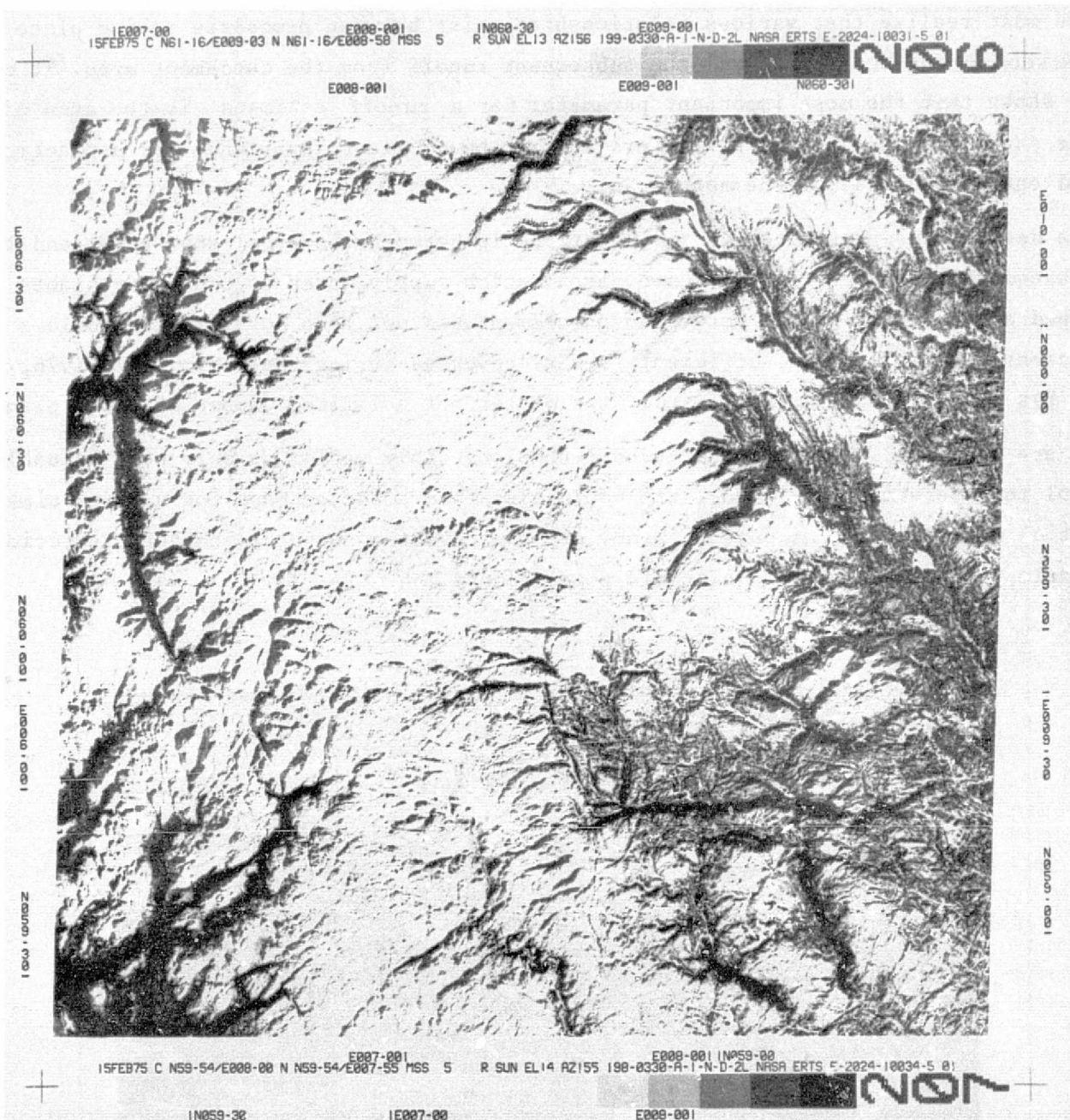


Fig. 2 The LANDSAT image 2024-10034, band MSS 5, taken on February 15, 1975, shows the mountain plateau Hardangervidda which is the main source for many hydro-electric power stations in this part of Southern Norway. The elevation ranges between 800 and 1800 m a.s.l. In spite of the low sun elevation (14 degrees) very few shadows are found on the mountain plateau. Most shadows are in the deep fjords on the western side and in the steep valleys of the eastern side of the main catchment areas. Power stations are mainly located in these depressions in the landscape.

the information onto maps. It must also be presented to the users in a form which they are used to obtaining such information, e.g. in tables etc. It is my hope that the work will be of practical value for the people who are responsible for water resources management.

One must realize that various relationships exist between processes taking place in the snow during the spring and the subsequent runoff from the catchment area. It can be shown that the most important parameter for a runoff estimate is the area of the snow cover. All other parameters seem to be of minor importance for a practical and operational use of the method.

The desired research to study the relationship between the areal snow cover and the subsequent runoff for all catchment areas which supply water to the power plants owned and operated by the Norwegian government has not been possible for obvious reasons. Due to lack of sufficient LANDSAT coverage during the period 1972-1976, it has been difficult also to study the matter for a limited number of power plants.

We are convinced, however, that such a complete study would not only be a valuable tool for operational purposes, but would also form a better base for various simulation models. Large amounts of money are now invested to obtain better prediction models for Norwegian hydro-electric power plants.



Fig. 3 Oblique air photograph showing part of the lake Røssvatn and snow-covered mountains within the drainage basin for the power station Røssåga. This picture is typical for most mountain drainage basins in Norway. Parts of the hummocky terrain are at lower levels, where the snow has partly melted away. More snow is remaining at higher elevations, whereas the snow cover is almost continuous in the high mountains. There is obviously no clearcut snowline!

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The following Norwegian hydro-electric power plants have been included in the study:

Name of power plant	Songa	Nore	Mår	Aura	Trollheim	Tun-sjødal	Ø. Røss-åga	Rana	Innset
Total head (metres)	264	343	780	760	370	230	123	506	175
Annual inflow (Mill.m ³)	870	1 510	562	995	910	1 548	2 720	1 615	1 009
Reservoir capacity (Mill.m ³)	750	687	581	757	384	1 171	2 559	2 326	1 027
Catchment area (km ²)	575	2 190	759	950	579	1 126	1 935	1 227	1 353
Annual production (GWh)	585	1 100	1 005	1 700	743	400	820	1 830	410

OPTICAL PROPERTIES OF SNOW

The intensity of transmitted radiation I is often assumed to attenuate exponentially with distance, x , according to the Bouguer-Lambert law:

$$I_x = I_0 e^{-vx}$$

where I_0 is the entrant intensity at $x = 0$ (corrected for initial reflection). The attenuation coefficient, or extinction coefficient, v , is the sum of the absorption coefficient and the scattering coefficient. It represents mainly the effects of absorption in clear ice, but in bubbly ice and snow the attenuation process is dominated by scattering from bubble surfaces of grain boundaries. We can assume that with diffuse incident radiation of optical (visible) wave lengths (0.4 - 0.7 μ m), attenuation below the surface of homogenous snow can be characterized by the extinction coefficient.

Spectral reflectance

The reflectance of snow is determined by the illumination conditions, by the characteristics of the surface, and by subsurface backscattering. With diffuse illumination (e. g. overcast sky) and with a smooth snow, a Lambert surface can be assumed (reflected intensity proportional to cosine of the reflection angle), and a simple value of reflectance defined. With direct sunlight the reflectance is also directional, especially if the snow surface has directional roughness characteristics. Although reflectance varies with wavelength, there is not much spectral selection in the visible range (snow looks white in "white" light), and a mean reflectance, or albedo, is often used.

Clear ice has a very low extinction coefficient in the visible range, so that a thick layer with a clean flat surface has very low reflectance; for visible light the reflectance or albedo is about 0.02, or 2%. In snow, the grain boundaries have a strong scattering effect, and diffuse reflectance values approach 100% for deep layers of fresh fine-grained material that has angular grains and little intergra-

nular bonding. For moist or wet snow the albedo can drop to the 0.6 to 0.8 range. The albedo decreases with increasing grain size, and the albedo will be inversely proportional to the square root of grain size. Most of the reflection of visible light occurs very close to the surface.

Measurements of spectral reflectance made in various parts of the spectrum, show a sharp falloff between 0.7 and 1.5 μm , and very low reflectance above 1.45 μm . At about 1.8 and 2.25 μm there are local peaks of reflectance that are most pronounced for fresh snow and fine grained snow. Local peaks in the reflectance curve correspond to the absorption spectrum of ice. Throughout the range, reflectance decrease with an increase of density and an increase of grain size. Thawing the snow to a wet condition reduces reflectance throughout the range, and refreezing does little to restore higher values. At about 2.0 μm , the reflectance of

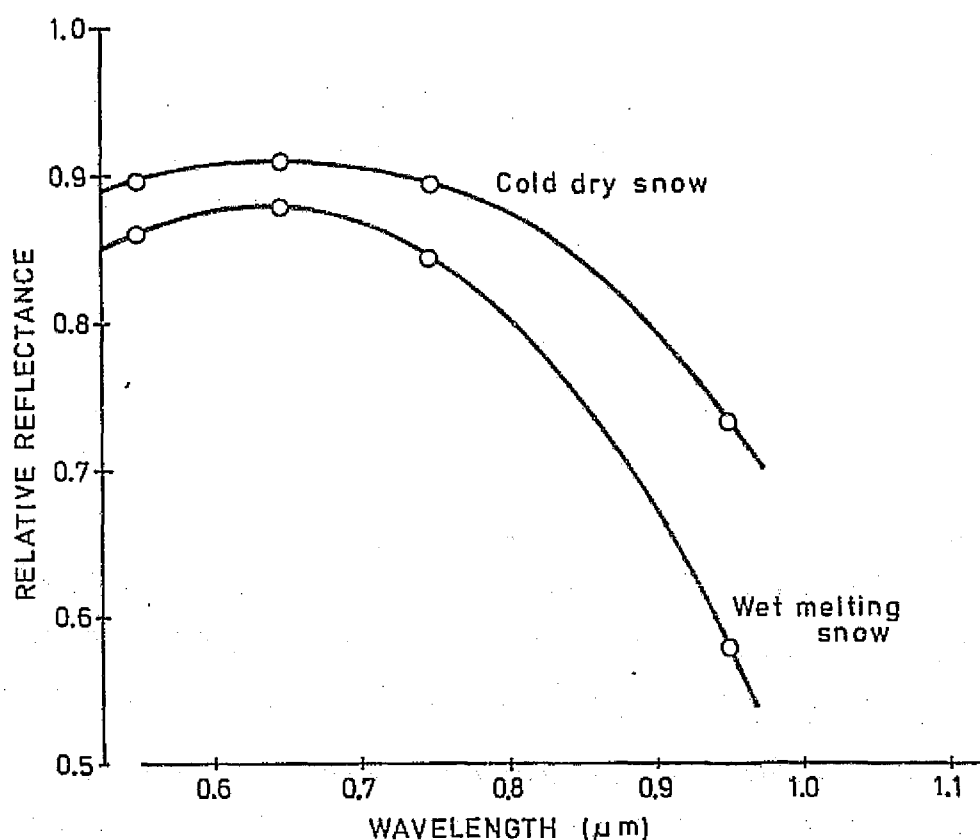


Fig. 4 The reflectance of various types of snow was measured by means of a densitometer on original 70 mm transparencies. Also CCT-data were used to obtain information to construct the curves shown in this illustration. The measurements were in all cases made on snow patches in sunshine. However, dry snow conditions occurred only in winter time when the sun had a relatively low position, so these data were obtained at low sun elevations.

Note that all data are obtained directly from LANDSAT data - not measured in a laboratory.

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thawed snow and refrozen snow is high in relation to fresh snow. The reflectance varies to some extent with angles of reflection. (O'Brien and Munis, 1975).

Measurements of spectral reflectance from 0.3 to 1.45 μm on progressively decaying snow for various sky conditions has shown that reflectance remains quite high throughout the range. In the near infrared there is a local peak at about 1.15 μm , and a local minimum near 1.3 μm , but almost all the values are above 50 % reflectance.

PHYSICAL PROPERTIES OF SNOW

Snow is defined as falling or deposited ice particles formed mainly by sublimation (UNESCO/IASH/WMO, 1970). It can also be described as the solid form of water which grows while floating, rising or falling in the free air of atmosphere.

Snow is formed when crystals nucleate, grow, and begin their descent to earth. While falling through atmospheric layers of varying temperature and humidity, the crystals can change form and size. When windy conditions prevail, snow crystals are carried along while held in suspension so that further modification by thermodynamic and mechanical processes is possible, especially near the ground.

The density of newly fallen snow is often as low as 0.1. A maximum density of 0.58 is very seldom exceeded even by wet, old snow.

Snow may eventually reach a density at which air permeability drops to zero, either by refreezing of pore water or by compaction during progressive burial. By convention, the material is then considered to have made the transition from "snow" to "ice".

Especially at temperatures near the melting point snow is a very complicated material. It is also a highly variable material, with some properties that change by several orders of magnitude as bulk density varies over the typical range for deposited snow. Nevertheless, the general properties of snow are fairly well understood, and the main problem is locating the relevant data. Snow mechanics still remains a somewhat confused field, optical characteristics could perhaps be better defined, and the properties of wet snow need more systematic attention. Satellite technology offers revolutionary possibilities for monitoring snow cover over vast areas, with immediate potential benefits in snow hydrology, provided the essential research on optical and dielectric properties are made.

SNOW MELT - SNOW LINE

For all of our larger power plants the catchment area is a rolling mountain terrain without or with only little forest. During the snow melt a certain "strand zone" is being developed parallel to the shoreline of the reservoirs. This zone will soon become dry. Above this belt we have an area of wet ground with only small patches of snow. Later we get areas of wet ground where the snow has just melted but the water has not yet drained away.

The next higher belt is partly covered with wet snow, and above this we find a continuous snow-covered area with only the highest points bareblown. Incoming radiation then melts the snow layers from the top and melt water percolates down making the snow layers isothermal and wet. There is no runoff from the bottom of the snowpack until this saturated situation has been reached. The determination of the heat conducted from the ground to the snow would require more information about ground temperatures. In deep snowpacks, however, this effect is usually considered very small - in any case insignificant for the runoff procedure.

When the snow cover has been reduced to about 60 centimetres (2 ft.) the sun radiation will start to pass through the snow, the dark soil is then heated and the snowpack begins to melt also from the bottom.

The melting effect of rain is small. The amount of snow melted by rain is proportional to the rainfall depth in millimetres and the temperature of the rain. Simple calculations can show that the energy impact of falling rain is negligible.

Convective heat transfer or turbulent exchange of heat which depends on the air temperature and wind velocity is an important factor in the energy balance. While the radiation balance is the main point of interest in glacier runoff studies, air temperature has been established as a useful index in practical calculations of snow melt runoff. At least it is in most cases available as a directly measurable value, or, if not, it can be extrapolated according to established relations.

There is some loss of water due to evaporation, but also some water gain due to condensation on the cold surface. Condensation and evaporation are functions of moisture and temperature conditions in the air. The water quantities added or removed from the snowpack by these processes are, however, comparatively small. The melting effect of condensation can be considerable since about 590 cal of latent heat are released for each gram of vapour condensed.

Exposure is another important factor since it governs the angle of the incident radiation. Contrasting patterns of snow cover due to a varying exposure are often observed at the end of the winter season when south-facing slopes are deprived of snow by

the low sun. Variations in albedo will also substantially affect the radiation balance. In most of Norway the winter snow covers the landscape almost quite down to sea level and there does not exist - during the most of the winter - any snow line (border between covered and uncovered ground) in the catchment area. It seems therefore that it is not possible to estimate the total amount of snow in an area of this type from LANDSAT images before the snow melt has started, and the snow line is well above the lowest point in the catchment basin. However, as soon as this situation has been reached, it seems possible and even advantageous to utilize LANDSAT images to monitor the snow melt.

The word snow line will be used many times in this paper and it is necessary that it is properly defined:

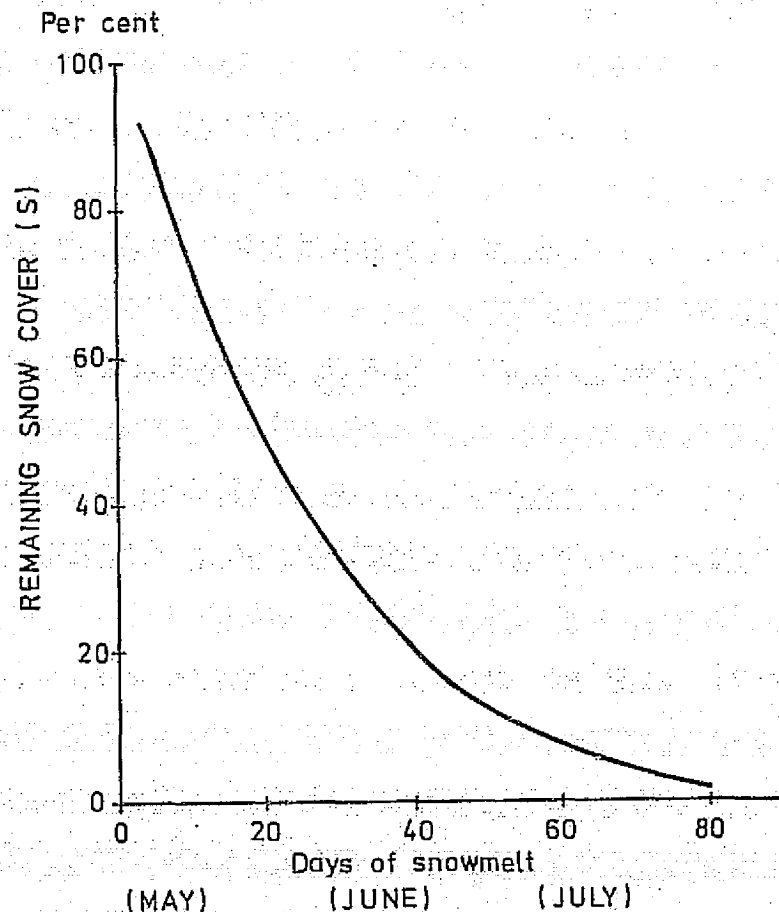


Fig. 5 The diagram shows the typical decrease in snow cover, given in per cent of the total catchment area, for the Røssåga drainage basin in Northern Norway. The snow starts to melt in May and, as soon as small parts of the basin become snow free, the snow-covered area decreases rapidly during the latter part of May and the beginning of June. In July there is a slower decrease in snow-covered area, possibly due to heavy snow accumulation in snow banks or patches of heavy snow caused by winddrift during the winter. There is almost no snow left in the area at the beginning of August. (See further text page 15.)

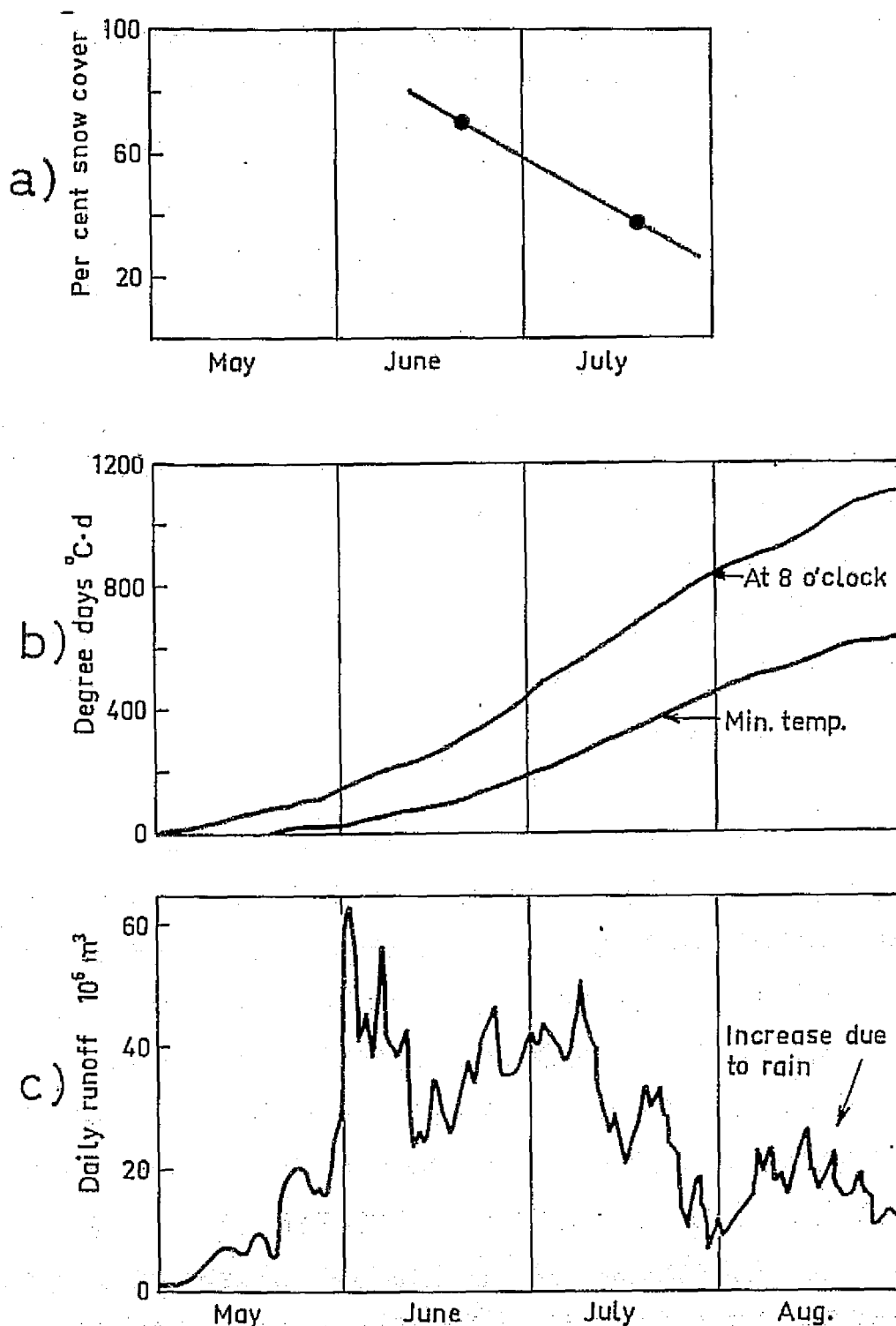


Fig. 6 Diagrams showing conditions at the Røssåga hydro-power system during the spring of 1973. The catchment is completely snow-covered in May; then - during June and July - the per cent snow cover decreases gradually, thus producing meltwater which drains into the reservoir.

- a) Per cent snow cover in the catchment determined from LANDSAT images.
- b) Cumulative temperature diagrams showing calculated degree-days, based upon the observed minimum temperature and the eight o'clock morning air temperature.
- c) Daily runoff, expressed in millions of cubic metres per day ($10^6 \text{ m}^3/\text{day}$).

Encyclopedia Britannica (vol 19, p. 303, 1974) defines snowline as follows:

Snow line, lower limit of perennial snow. The snow line is an irregular line located along the ground surface where the accumulation of snowfall equals ablation (melting and evaporation). This line varies greatly in altitude and depends on several factors. On windward slopes and those facing the afternoon sun, the snow line may be as much as a kilometre higher than on opposite slopes. Over larger areas, summer temperatures and the amount of snowfall determine the position of the snow line. Where temperatures are cold, as near the poles, the snow line is quite low; where temperatures are warm, as near the Equator, the snow line is very high. In moist coastal areas with much snowfall, the snow line is lower than in areas of dry continental climates because of differential ablation; the snow line in the dry horse latitudes is higher than at the Equator, where there is more snowfall for the same reason. Average altitudes of the snow line taken over large areas can be used to derive a climatic snowline. This rises or falls in altitude in response to worldwide climatic change. During glacial periods, the climatic snow line was from 600 to 1,200 metres (2,000 to 4,000 feet) lower than at present.

RATE OF RUNOFF

Fig. 6 shows the effect of snow cover on the melt water production from a mountain basin. The snow cover remains close to 100% for a time and then the meltwater from the area varies according to the temperature pattern. Then the snow cover gradually decreases and this continues to the end of the snow melt season. The melt water from the basin, or the basin snow melt rate, is already on the decline before the summer temperature reaches its maximum value. The characteristic form of the snow cover depletion curve is related to the pattern of the hypsographic curve of the basin.

It was shown by Leaf (1967) that

$$A = \frac{100}{1 + e^{-bt}}$$

where

- A = percentage of area without snow
- t = time (days) measured from an arbitrary origin
- b = a coefficient
- e = the base of natural logarithms

When working with data from the Røssåga area we found the following expression to best describe the observations:

$$S = \frac{200}{1 + e^{0.055t}}$$

S = percentage of snow cover

This expression will then give the snow cover in per cent for a given time t days after that the reduction of the snow-covered area started.

INTERPRETATION OF LANDSAT DATA

One of the basic ideas of remote sensing is to measure the different spectral signatures of different objects. This interpretation of remote sensed data makes it necessary to understand spectral properties of different ground objects. An ideal situation would have been if one had a library of the signatures of different surfaces at different times of the year and with different illumination. This is, however, not available at this stage. Much work has to be done before we fully understand the process of reflection from various objects.

Also for the material snow, we have not yet got a thorough knowledge of different types of snow as viewed by LANDSAT under varying light conditions, sun angles, etc.

When selecting test areas for the LANDSAT-2 experiment, we tried to find areas spread over the entire country. However, we soon realized that all available material obtained by LANDSAT 1 and 2 would be too small for our purposes. The main reason for this is that the important period for snow inventories is June - July and a satellite pass every 18 day gives only 4 possible passes during this two-month period. Overcast weather on some of these days, or if only parts of the test area is visible, or difficulties with the tape recorder onboard the satellite can destroy all possibilities to make any useful work that year.

We have for the period 1972 - 1976 been able to obtain data for 9 power plants and a total of 15 images have been used for our snow mapping experiment.

WORK PROCEDURE

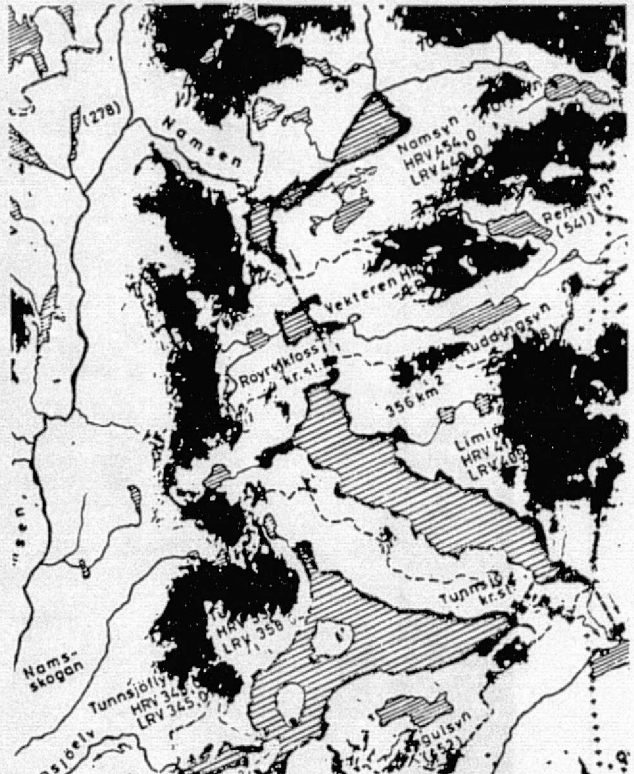
We have tried to find a method for snow mapping which can be applied under the special conditions we have in Norway, where mountains are different from the Alps. Norwegian mountains are generally forming a gently rolling country, with many highmountain plateaus, and mostly little shadows. The forest in Southern Norway reaches an elevation of 800 m (2 500 feet) which means that the most important catchment areas are above the tree limit, compare Fig. 2.

The method we have found most valuable during the LANDSAT experiment is simple and based on the use of material which is readily available in most offices:

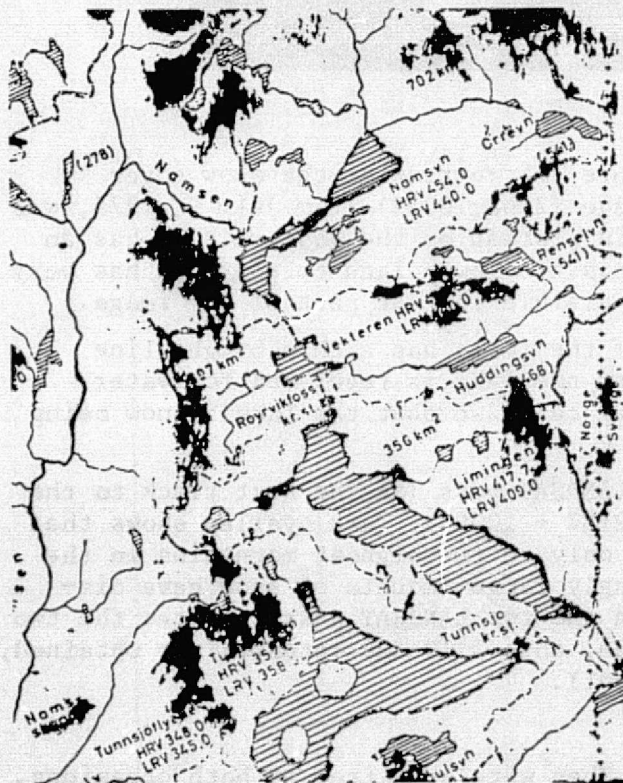
1. An enlargement of a part of the MSS 5 image is produced at a scale of 1 : 200 000 - 1 : 400 000. This print is made darker than normal, so that every little snow-patch will stand out clearly.
2. A clear acetate sheet with an outline of the catchment area and easily identifiable lakes marked on it is placed upon the paper print.



a)



b)



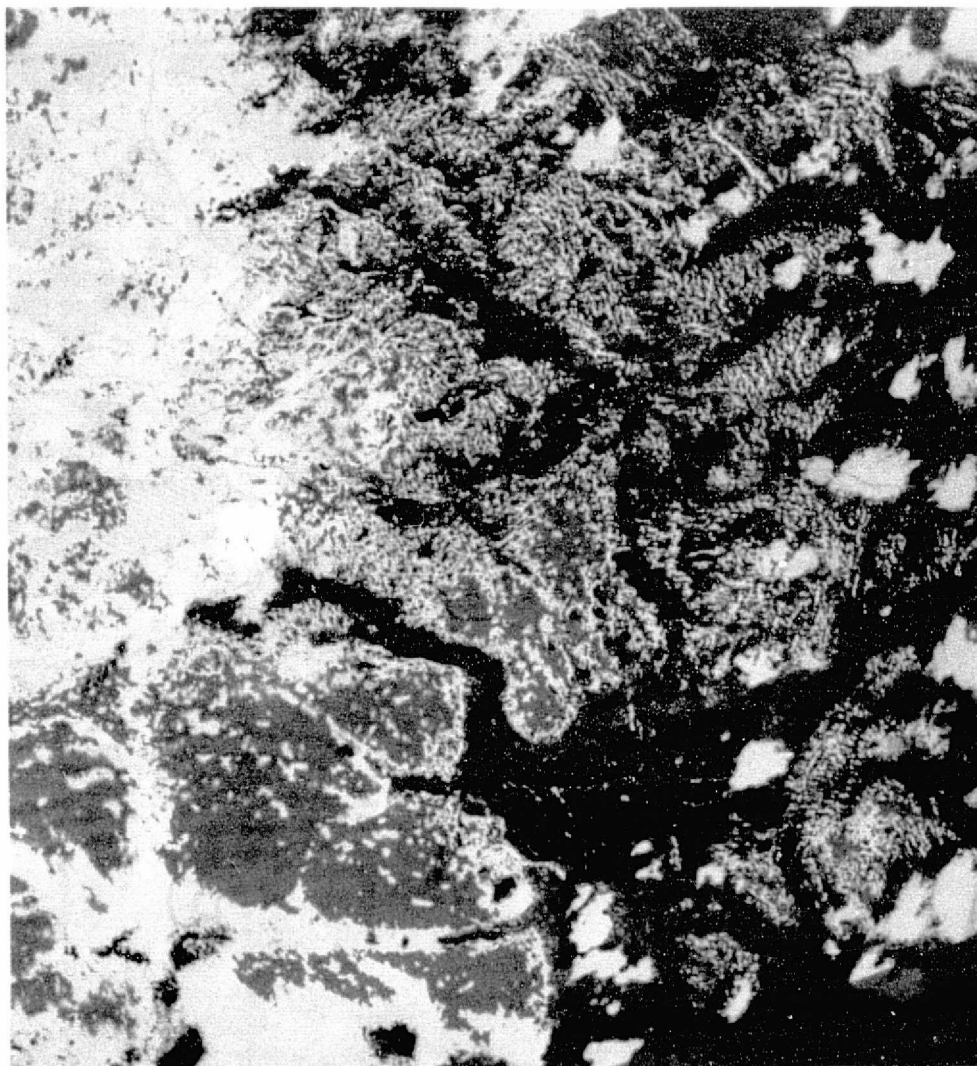
c)

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Fig. 7 A catchment area draining to the river Namsen is shown on the map. Overlays were produced from three LANDSAT passes, viz.

- a) June 20, 1973 (1332-10022)
- b) July 9, 1975 (2168-10014)
- c) July 27, 1975 (2186-10012)

The overlays were produced by a photographic method so that all snow-covered areas (black) were emphasized on a transparent material. It can be seen from this series that a substantial snow melt normally takes place in July.



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Fig. 8 An experiment was made to demonstrate the retreat of the snow cover between two LANDSAT passes. One image (2168-10032) from July 9, 1975, was enlarged. It shows that the mountain plateau on the western side has an almost continuous snow cover, whereas the lower land to the east has very little snow. Only a few clouds are visible in that part of the image.

The lake Møsvatn near the centre of the image has a thin bright line along the shore which indicates that the lake is regulated for water power production. The conclusion can be drawn that the lake is now being filled by snow melt water.

An overlay was made from the next LANDSAT pass (in the next track to the west) on July 28, 1975 (image No. 2187 - 10084). This overlay shows that a continuous snow cover is present only on the highest mountains in the western part of the area. Surprisingly large amounts of snow have disappeared during the 19 days between the two LANDSAT passes. (Note: the two images are overlapping the test area, thus a 19-day interval was obtained, instead of the normal 18-day interval).

Legend:

- Black - Land and water surfaces. They were snow free at both occasions.
- White - Dots are clouds.
Continuous white areas indicate land surfaces where snow has disappeared during the 19-day period from June 9 to July 28.
- Grey - Snow still remaining on July 28, 1975.

3. An overlay of clear, translucent regular squared paper (for example 5 x 5 mm squares) is placed on the paper print. The photographic image is clearly visible through the overlay.
4. The snow-covered area is determined by simple counting of squares and expressed either in km^2 or in per cent of the entire catchment area, compare Fig. 7.

This procedure is very quick and the accuracy obtained is within the limits of the other measurements made. Uncertain factors are the amount of water which is under way through the soil (groundwater), the precipitation during the period for which the planning is made, and the evapo-transpiration from the soil and the snow surfaces.

A graph is established for every catchment area as data becomes available the first time. The graph should contain values that can be easily compared for different areas.

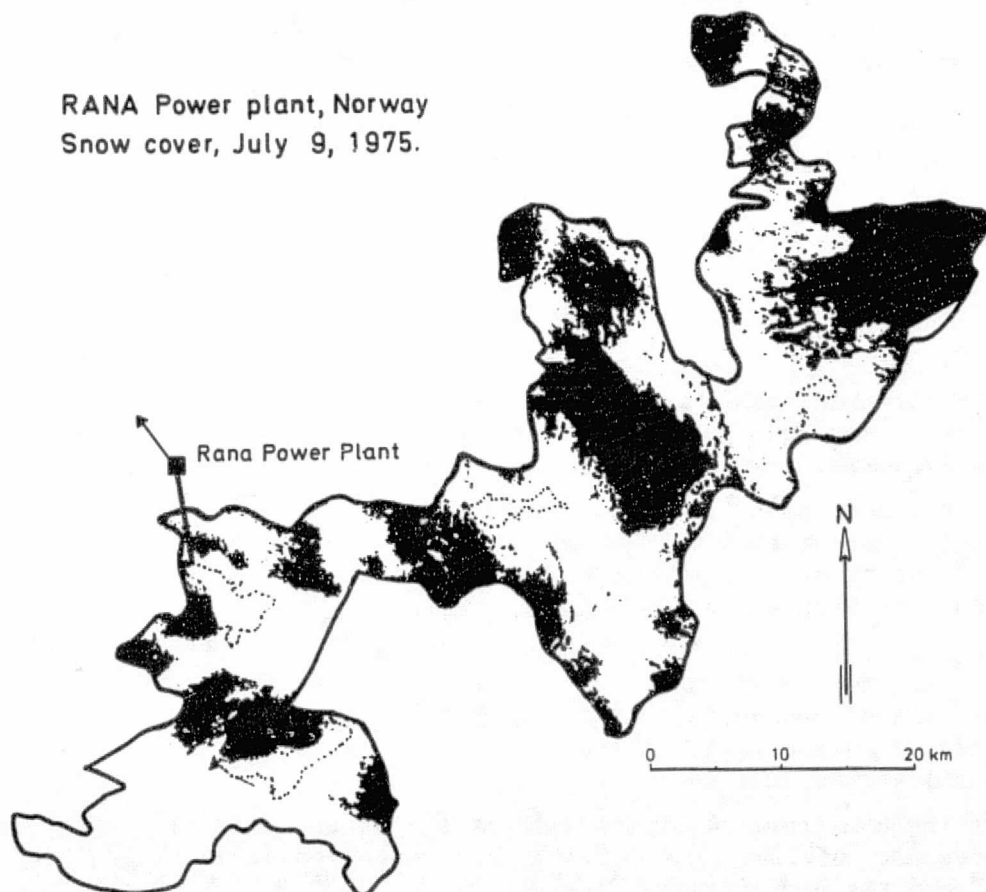


Fig. 9 The snow-covered areas in the Rana drainage basin were mapped from LANDSAT MSS 5 by the use of a thermocopying process. All snow areas - i.e. areas brighter than a certain brightness level - were made black and overlayed onto a standard map of the basin. In this procedure it was necessary to use lake surfaces for registration. These lake areas are marked by dotted lines on this sketch. The total snow-covered area was 650 km^2 on July 9, 1975. This figure could be used for melt water prediction according to a curve similar to that shown in Fig. 8, provided such a graph had been constructed for this catchment.

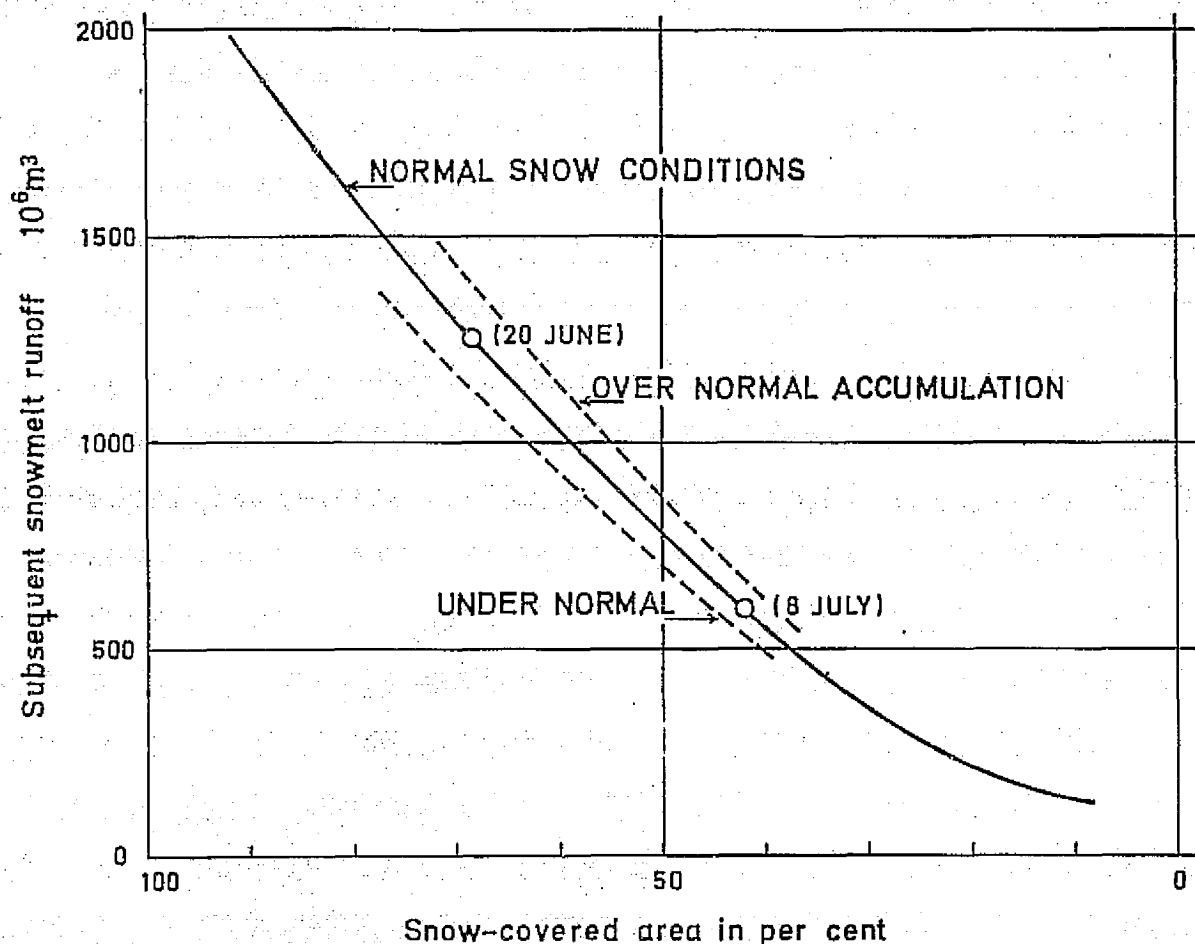


Fig. 10 The catchment basin for a relatively large power plant in Northern Norway (Røssåga) has been studied in some detail. Its total area is 1935 km², almost entirely above the tree line.

It has been possible to construct a graph which can be used for prediction of snow melt runoff from this catchment, provided observations of melting snow cover are made after that at least 5 or 10 per cent of the area has become snow free.

The heavy line can be used for runoff prediction after a winter of normal snow conditions. For example, if the snow covers about 70 per cent of the basin, one can expect 1300 million cubic metres of water to drain from the remaining snow. This situation is normally found around June 20.

If the snowcover is 50 per cent in the basin, this will normally give 800 million m³, etc. Such a situation is normally found around the beginning of July.

The two stippled lines indicate that a smaller runoff is expected after a season with little snow accumulation, and a higher runoff after heavy snow winters. These lines are extremes, during most of the years a curve made closer to the solid line can be used. However, the exact location of it has to be decided by subjective judgement or from ground truth data obtained at selected snow courses in the basin.

NOTE: This graph is valid for the Røssåga basin only, but graphs made for other high-mountain basins have the same general shape - compare Fig. 11.

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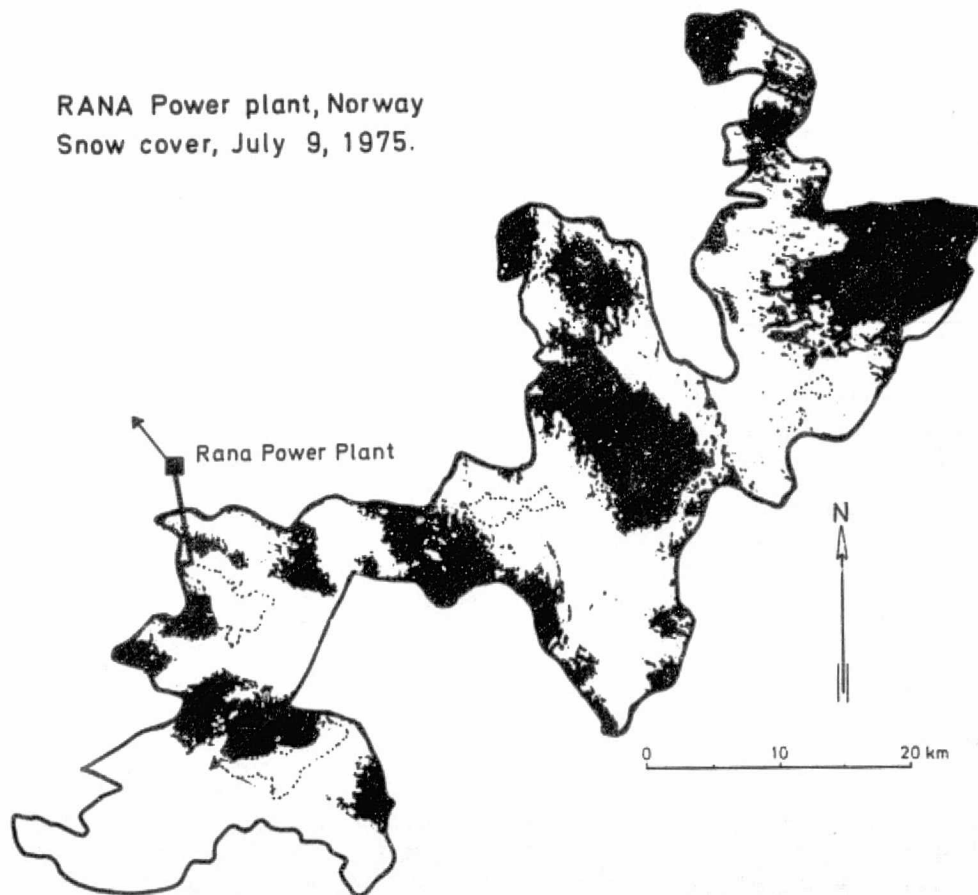


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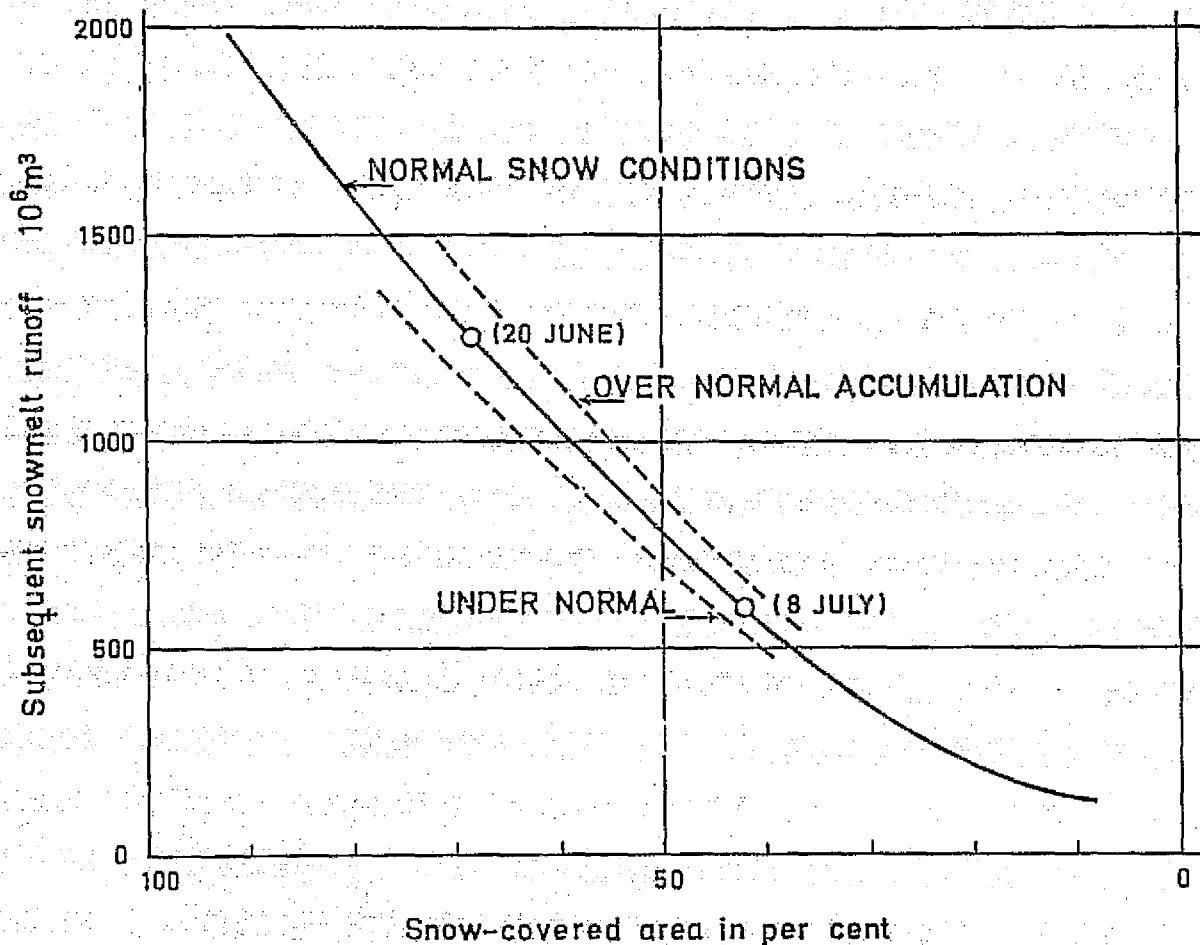


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NOTE: This graph is valid for the Røssåga basin only, but graphs made for other high-mountain basins have the same general shape - compare Fig. 11.

Our experience is that it is most useful to plot the following parameters in the graph:

- "Subsequent runoff", expressed in millions of cubic metres (10^6m^3) This concept is regarded as a dependent variable and is plotted on the Y-axis.
- Snow covered area, expressed in km^2 , is regarded as an independent variable and is plotted on the X-axis. See Fig. 11.

A somewhat simplified method is shown in Fig. 10.

RESULTS

The area of snow cover and the measured and corrected subsequent runoff was plotted separately for each area. It was soon found, however, that the data for the different areas could be plotted advantageously in the same graph, and a curve could be fitted through these points with relatively small deviations. We were also a little surprised to find that areas in the south had nearly the same runoff characteristics as areas in the north although the climate is entirely different.

The result of this work is shown in Fig. 11 and the curve that could best be fitted to the data, can be expressed:

$$Q = 128 (e^{0.0018 A} - 1)$$

Q = subsequent runoff (10^6m^3)

A = snow-covered area km^2

It means that for any area which has the same characteristics as the test areas the subsequent runoff (Q) can be determined when the snow-covered area (A) is known.

Experience has shown that if the extent of snow cover is determined from all four LANDSAT bands, there are significant differences in the results. MSS 4 gave the largest snow cover, but only slightly more than MSS 5, whereas MSS 6 and MSS 7 gave the smallest snow area.

A study has been made, using meteorological observations, to show that there is a relationship between the last date of snow fall and the area covered with snow, as determined from the different bands. Imagery obtained shortly after a snow fall showed no significant difference in the snow-covered area when the four bands were compared, whereas a pronounced difference in snow-covered area was found in images taken after a long period without precipitation.

The MSS 5 data appear to be the most useful of the two lower bands for snow mapping. In some of the MSS 4 images the snow-covered areas are in fact near saturation, and

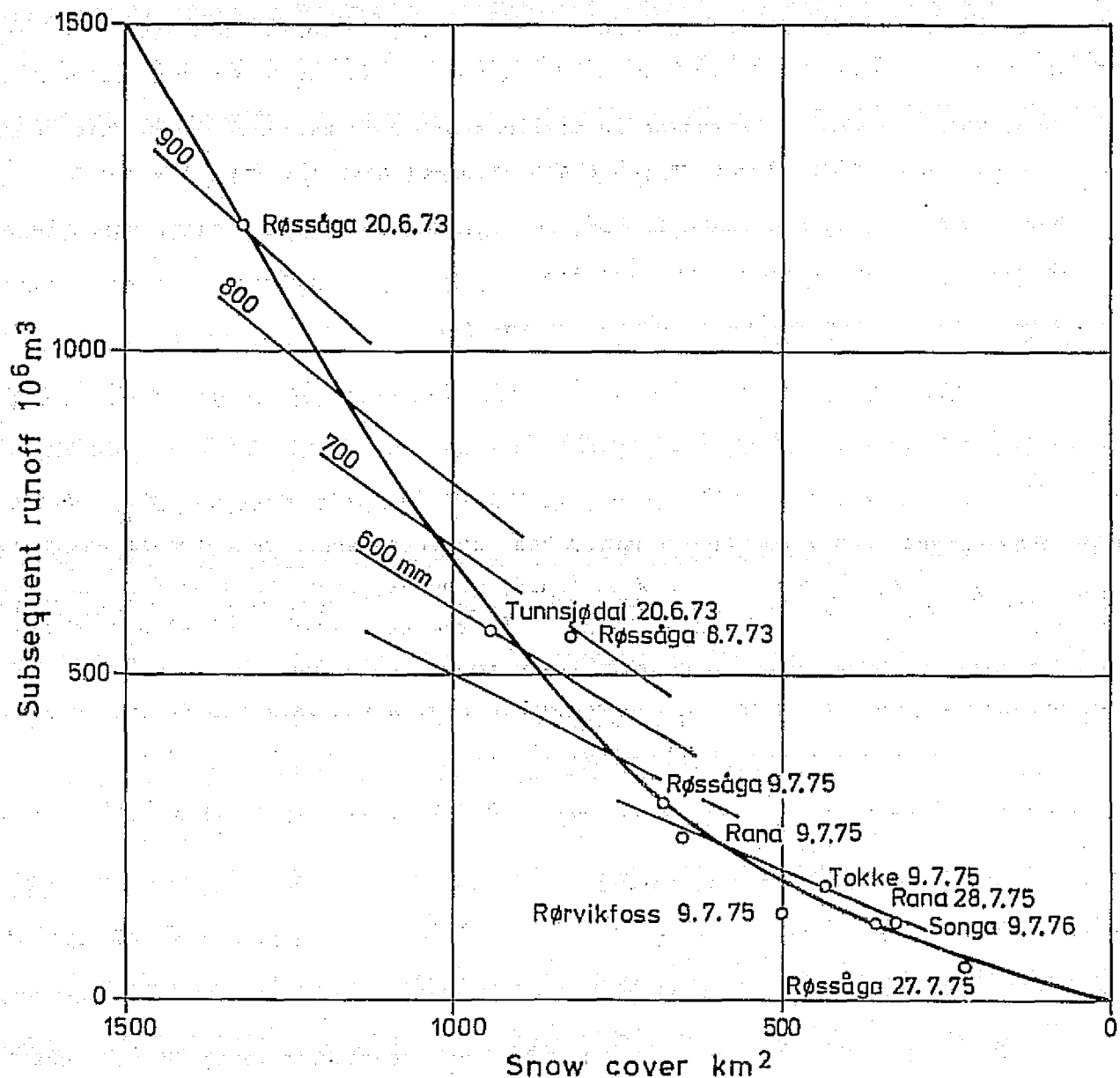


Fig. 11 Experience has shown that it is possible to combine results obtained at various power plants in Norway in the same diagram. Subsequent runoff is plotted as a function of snow cover. Note that instead of calculating the percentage of snow cover in the catchment, it seems sufficient to determine the snow-covered area in square kilometres. The expected subsequent meltwater runoff can then be found directly from this generalized graph (heavy line) independent of the size of the total catchment area.

It is obvious, however, that the same curve may not be used year after year due to variations in snow cover thicknesses (or snow density). It could be necessary to draw several, more or less parallel, lines in the same diagram - the upper of which would indicate the situation during years of exceptionally heavy snow cover and the lowermost would show the situation in years of very thin snow cover. Such a variety of diagrams have not been constructed yet. However, to make it possible for the investigator to have a feeling of the situation and the processes which takes place in the snowpack within this catchment, certain thin lines are drawn in the diagram. These lines indicate the specific water equivalent

(continues next page)

this might cause a loss of detail in the snow pattern. The MSS 7 which has been found to be extremely useful for studies of glaciers and sea ice in the Arctic, may provide useful information for certain purposes in snow studies, such as detecting melting conditions, etc., but is not very suited for estimation of the size of snow-covered areas.

A limited number of colour composites have also been examined. The conclusion is that such images have little advantage and give little new information for detecting and mapping snow cover.

All values should be corrected to give the runoff with "normal" precipitation as this will make it simpler and quicker to use the graphs in the future. In the period June - July the precipitation is normally low, mostly in the order of 14 - 18 per cent of the annual precipitation, so that possible yearly variations will not disturb the results significantly, but some corrections should be made accordingly.

It should be mentioned that within well regulated reservoirs (where the relation between reservoir capacity and annual inflow is more than 60 per cent) the exact time for expected start for snow melt runoff is not significant and it is not really too important to know when the snow is wet and "ripe". Typical for the work

(continued)

of the remaining snow in the catchment. For example, the line marked 700 is constructed in the following way: take $700 \cdot 10^6 \text{ m}^3$ on the Y-axis and $1\,000 \text{ km}^2$ on the X-axis. Draw through this point a straight line to the origin.

An example will show how this diagram should be understood: At the Røssåga catchment it was found on June 20, 1973, that 1330 km^2 were snow-covered. During the melt season in total $1200 \cdot 10^6 \text{ m}^3$ meltwater drained from the area. Consequently, the water equivalent of this snow averaged

$$\frac{1200 \cdot 10^6}{1300 \cdot 10^6} = 0,902 \text{ or } \underline{902 \text{ mm of water equivalent}}$$

Later in the season, on July 9, the same catchment had almost 700 km^2 snow coverage, and the subsequent runoff amounted to $300 \cdot 10^6 \text{ m}^3$ water. By a similar calculation it can be found that the remaining snow had now a specific water equivalent of approx. 429 mm, i.e. the snow cover had become substantially thinner!

By drawing these lines it is possible to follow the decrease in average water equivalent of the remaining snow in the catchment and it has proved useful to construct such a diagram, but the information plotted on the thin lines are, in fact, not used directly in the forecasting procedure. However, they may give the investigator a better feeling of the snow melting procedure.

with this method is that the snow is wet, and it gives off meltwater more or less continuously. It is not possible to use the method before part of the catchment area is uncovered and the snow cover has started to shrink.

As mentioned above, it is possible to construct a graph which gives the relationship between snow cover (in percent) and the subsequent melt water runoff for one particular high-mountain basin.

For operational use, one would think that it is necessary to construct one separate graph for each individual basin, but according to our experience so far it is assumed all such graphs seem to have a common characteristics, which can be explained as follows:

If the snow cover seen in the spring in Norwegian high mountains (which are, incidentally, different from those in Switzerland) has a certain, given area extent, this "amount" of snow - expressed in sq.km - will normally produce a certain amount of water. I.e. if a watershed has a total area of 1000 km^2 and its snow cover is determined to be 50 per cent, this means that there is 500 km^2 snow present, which will (according to our experience) give about $200 \cdot 10^6 \text{ m}^3$ of melt water.

Another basin, 2000 km^2 in size is thought to have only 25 per cent snow cover, which is in fact the same "amount" of snow (500 km^2) which again give $200 \cdot 10^6 \text{ m}^3$ of melt water.

Consequently, it seems possible to construct one single graph which can be used for most high-mountain basins in Norway. The method of its construction is shown on page 22.

APPLICATIONS

The sloping lines in Fig. 11 are the equivalent water contents of the remaining snow in millimeters and is the result of dividing volume of runoff by the area. The curve indicates that when the snow area changes from 1300 km^2 to 1000 km^2 , the runoff will be $(1200 - 650) = 550 \text{ mill m}^3$ and the average water equivalent of the remaining snowpack has changed from 900 mm to 650 mm. This will of course not be quite correct because some of the water has left the snowpack and is on its way through the soil and some will be lost to the air. But this way of looking at the problem makes it easier to understand what is taking place in the snowpack.

A word of warning should possibly be given about the danger of overestimating the snow cover! During snow melt the snow retracts and the ground underneath becomes exposed to daylight. This surface is normally covered with dead, brown vegetation which partly covers the underlying soil. In the 0.6 - 0.7 μm range (MSS 5) both uncovered soil and rock surfaces have a high reflection. Such surfaces can easily be mis-interpreted as being snow surfaces, unless the paper prints are made exceptionally dark. The same soil surfaces will of course become dark on the images as soon as we get a little green grass with chlorophyll (which is highly absorbent in the 0.6 - 0.7 μm range).

SPECIAL APPLICATIONS FOR GLACIERS

General

The Hydrology Division of the Norwegian Water Resources and Electricity Board is responsible for all observations of hydrological data in Norway and for the subsequent handling, processing and storing of the data. A new unit, the Glaciology Section was created within the Hydrology Division in 1962, and glaciological observations were immediately started at selected glaciers. During the following years the program was gradually extended, additional glaciers were included in the group of glaciers under study, whereas single glaciers were excluded when a certain amount of data had been obtained.

Detailed topographic maps were made of all the selected glaciers under study, mainly at a scale of 1:10 000. The field work included accurate snow surveys throughout the winter and, particularly, a complete snow inventory at the end of the accumulation season. During the melt season a variety of observations were carried out, normally by a crew based at the glacier, comprising water discharge measurements, meteorological observations, detailed measurements of glacier ablation, ice movement, etc.

All field data were processed so that the resulting figures from the mass balance investigations expressed the total accumulation and the total ablation in cubic meters of water equivalent. A "balance sheet" was then constructed for each of the observed glaciers. In the resulting table, the accumulation and ablation (reduced to "specific" values given in centimeters of water equivalent) were shown for selected elevation intervals of the glaciers. Finally, a calculation was made of the total mass balance for each glacier.

Influence of glaciers on river hydrology

If the glacier's mass balance is positive, it means that the glacier has gained mass, i.e. it has grown in volume, and, consequently, the stream draining from the glacier had carried less water than if the glacier had been in a "steady state" condition. Similarly, a negative mass balance means that the river receives more water than it should have done from the annual precipitation only. An "extra" amount of water is then delivered by the glacier's retreat. This water may have fallen on the glacier in solid form many decades or centuries ago.

It is well known that most glaciers in Norway (and also in other parts of the world) have decreased in volume during the last decades and they have thus provided the rivers with "extra" amounts of water almost every year. Consequently, if a power station is planned and designed according to statistics from the last decades, it might be over-dimensioned because the annual discharge shown in the tables is incorrect — it is definitely larger than it would have been if no glaciers were present in the basin. It is, therefore, of great importance to study glacier mass balance in areas considered for future water power development. Corrections of observed runoff data (particularly reduction for extra water supply from shrinking glaciers) can be done only by the use of glacier mass balance data.

The cost of glaciological studies are relatively high due to the need of extensive field work which is more expensive than most other field work within hydrology. The studies are, therefore, limited to a small number of glaciers simply for financial reasons. These glaciers must be selected carefully to obtain data which are representative for larger areas. It would be impossible, for practical and financial reasons, to observe all glaciers within large catchments intended for future hydro-electric power plants. We have, therefore, in Norway selected some "key" locations, one of them is the Nigardsbreen outlet glacier on the eastern side of the Jostedalsbreen ice cap in South-western Norway.

The transient snow line

It is obvious that the largest melt takes place during the summer on the lower part of the glacier, i.e. on the so-called "tongue". This means that the lower part of the glacier becomes snow free first so that the solid glacier ice becomes visible. The border between uncovered ice and still snow-covered areas of the glacier moves slowly up to higher elevations throughout the melt season. At the end of the summer this border, most often termed "transient snow line", reaches a height which is roughly near the middle of the glacier. In years of very high melt — mainly years of dry, hot summers — the transient snow line may reach much higher altitudes. When this happens, the glacier must have produced more melt

water than normal, and it has experienced a year of negative mass balance. On the contrary, if a summer has been cold (often cold and wet - i.e. with frequent snowfalls in higher areas), the transient snow line does not reach its normal altitude, i.e. the glacier has had a positive mass balance, and this again means that the glacier has produced less melt water than normal. See Fig. 12.

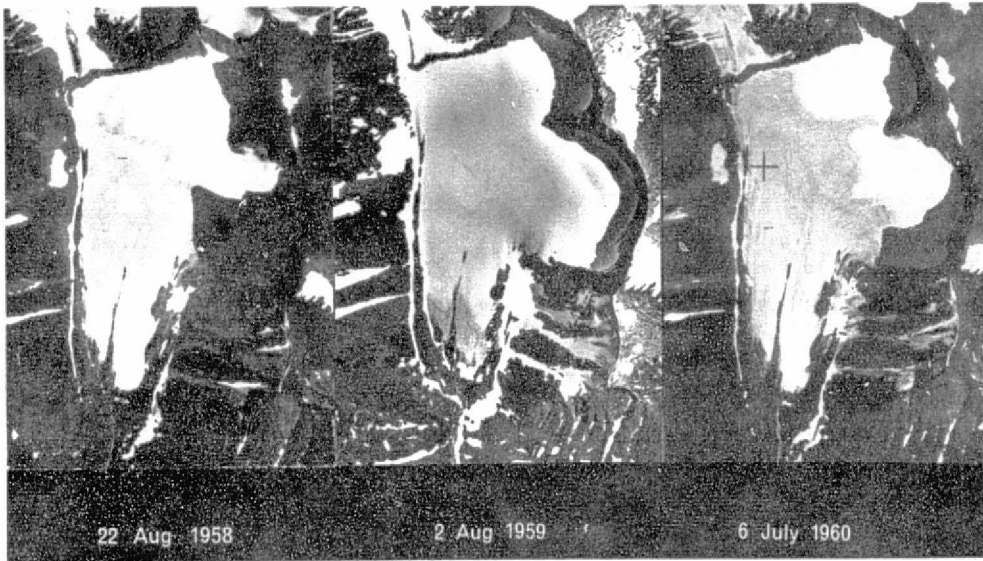


Fig. 12 The transient snow line is clearly visible on this glacier, photographed at three various occasions. It can be concluded from these pictures that the summer of 1959 must have been relatively cool (the transient snow line is situated at a low altitude, down on the glacier tongue). Similarly, the 1960 summer was unusually hot, so that almost all winter snow had melted away already at the beginning of July, and thus it is likely that the streams would receive more melt water than normal from glaciers in this region in 1960. The transient snow line climbs up glacier during the summer, reaching its highest altitude in August/September.

Experience from measurements made on many different glaciers in various countries indicates that there is a simple, linear relationship between the height of the transient snow line at the end of the summer and the glacier's mass balance. Consequently, if the height of the transient snow line is accurately determined at the end of the summer, this information can be used to determine the glacier's mass balance, provided the above mentioned linear relationship is known. Compare Fig. 13.

NIGARDSBREEN, Norway
1962-72

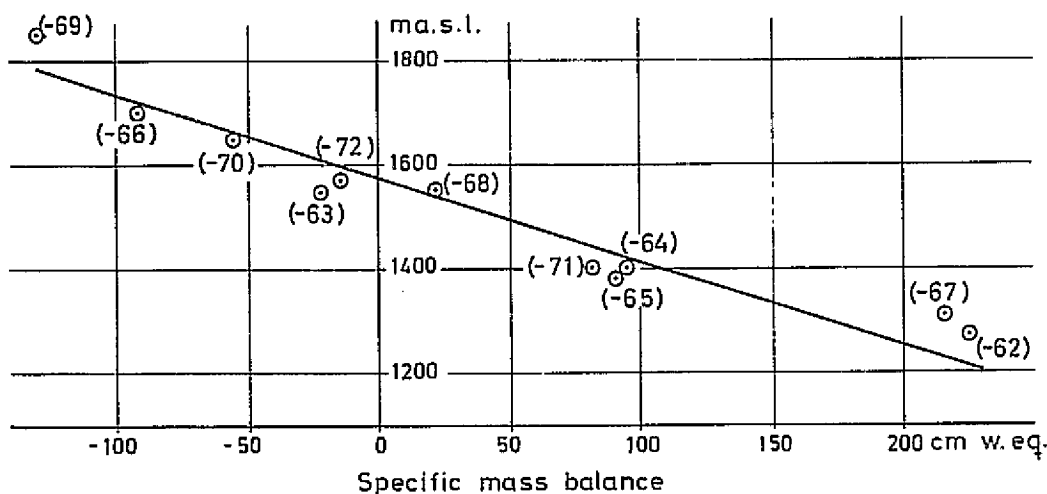


Fig. 13 Extensive field work, including detailed snow surveys in the spring and continuous observations of glacier melt during the summer, made it possible to calculate the height of the equilibrium line on the Nigardsbreen glacier. This height is here plotted vs. the mass balance, expressed in a specific water equivalent figure (Example: +50 cm means that the glacier has gained a mass corresponding to a 50 cm thick water layer all over its surface).

The equilibrium line, determined by glaciological methods, is, on most Norwegian glaciers, practically equal to the transient snow line, as observed at the end of the melt season, compare Fig. 12. This snow line can be seen on most LANDSAT images, compare Fig. 15.

Until now it has been impossible to observe the position of the transient snow line at the end of the melt season except for a small number of glaciers. An increase in the number of such observations, for example by means of space-acquired imagery, would enable us to monitor the behaviour of many more glaciers. This would greatly increase the practical usefulness of glaciological investigations, so efforts have been made to start experiments with satellite data. An area in Western Norway, focused on the Jostedalsbreen ice cap (the largest ice body in Continental Europe) was selected as one of the test areas, see Fig. 14.

The study of LANDSAT images during the last years has shown that it is possible to determine the height of the transient snow line with sufficient accuracy from such images. However, a great problem has been to obtain data from the correct time of the year, i.e. just at the end of the melt season. When, in the future, this will be possible, one could use the LANDSAT data for a quick determination of the height

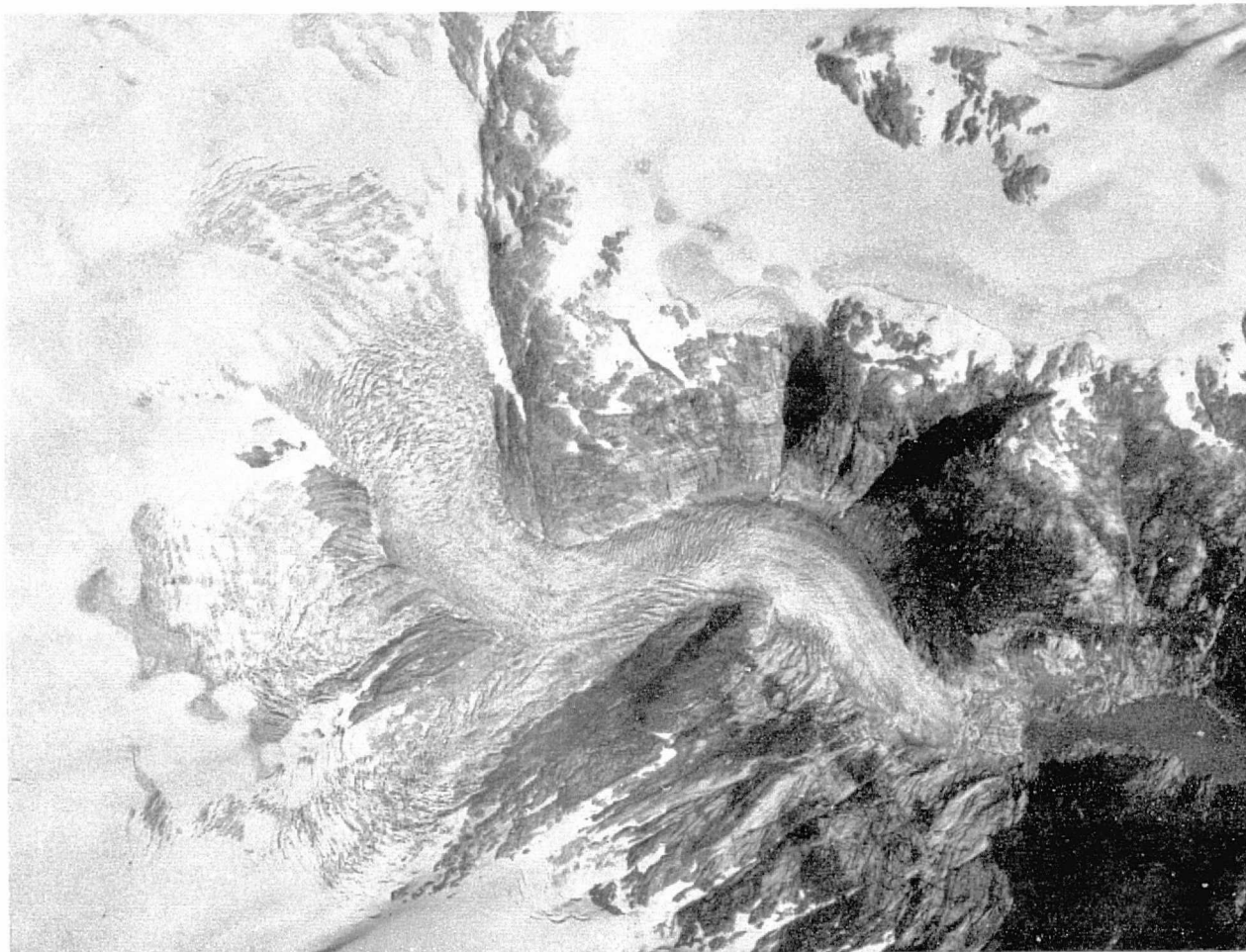


Fig. 14 Vertical air photograph of the outlet glacier Nigardsbreen which drains part of the Jostedalsbreen ice cap. Note that the lower section of the glacier consist of exposed ice, whereas the higher sections (left and upper parts of photograph) are still snow-covered. The transient snow line is defined as a line which can be drawn between these two kinds of glacier surface. However, it may be difficult to define this line exactly, particularly in heavily crevassed areas, as on this picture.

The lake Nigardsvatn can be seen to the right.

Nigardsbreen has been continuously studied in detail since 1962, and was selected as one of the test areas for LANDSAT experiments.

Picture taken by Fjellanger-Widerøe, Mission No. 4409, on August 29, 1974. Approximate scale 1 : 35 000.

of the transient snow line and thus obtain mass balance information at a much lower cost than ever before.

The evaluation of images can be made directly from photographic enlargements. We have, however, mostly based our snow line high determinations on color composite images produced in an additive color viewer because a higher contrast can thus be obtained, and better height determinations made. See Fig. 16.

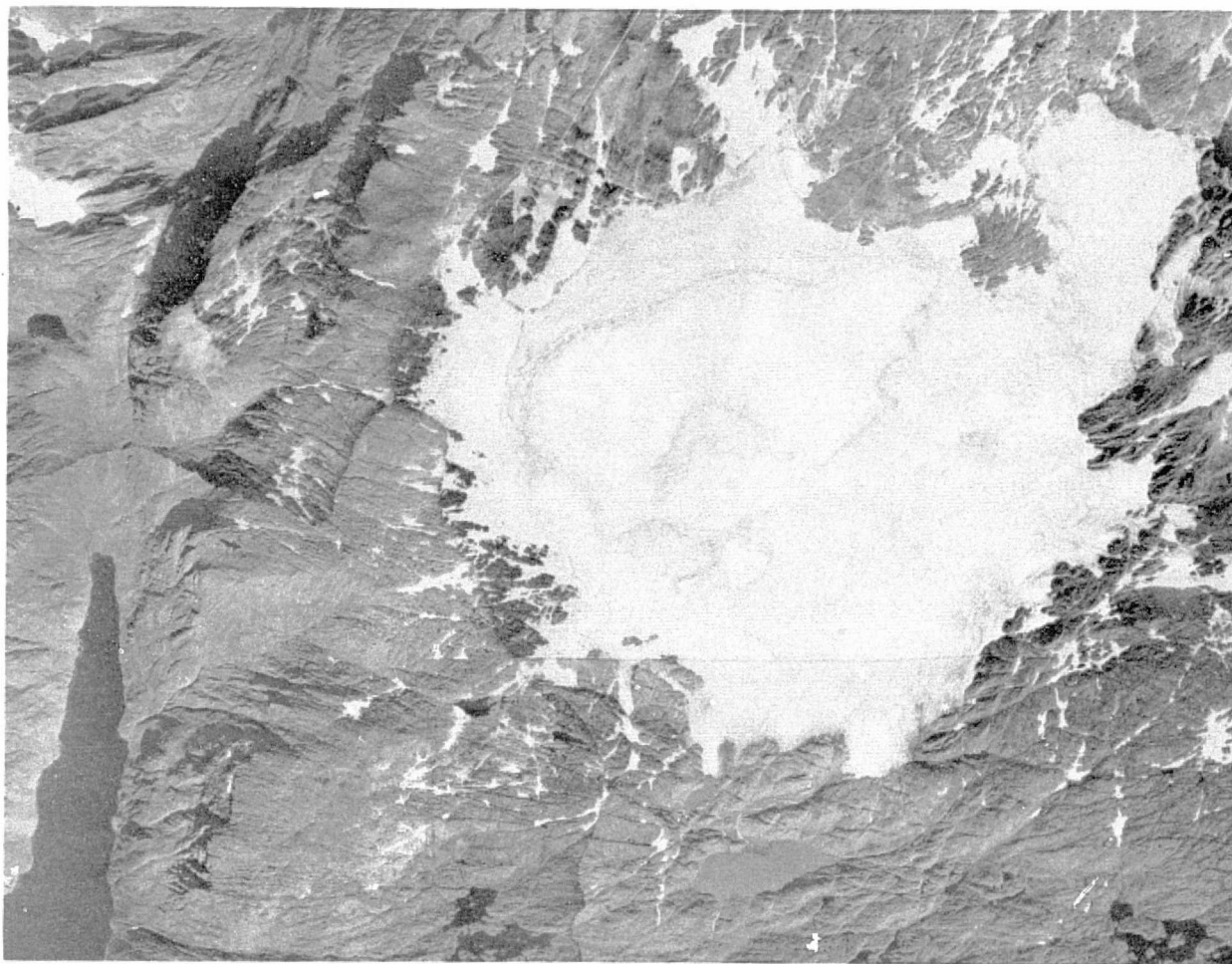


Fig. 15 Vertical air photograph of the small ice cap Seilandsjøkulen, the northernmost glacier on the European continent, situated at $70^{\circ} 25' N$. Its total area is about 14 km^2 .

The transient snow line is well defined, remaining white snow is still covering the highest part of the glacier, whereas uncovered glacier ice has a more grayish colour. Most of the glacier is draining to the south (downwards on this picture).

Several lakes can be seen, some of them receive melt water from the glacier and appear grey on the picture due to the sediment content of the melt water. Those which are not receiving melt water appear black on the picture.

The inner part of a fjord is seen at the lower left corner of the picture; this fjord can be used as reference when comparing with Fig. 16.

Picture taken by Fjellanger-Widerøe, Mission No. 3615. on August 14, 1970. Approximate scale 1:50 000.

Also computer printouts have been tried with a very good result (see enclosed example Fig. 17, from one of the outlet glaciers from the Jostedalsgreen ice cap). However, the work involved and the computer time used does not sig-

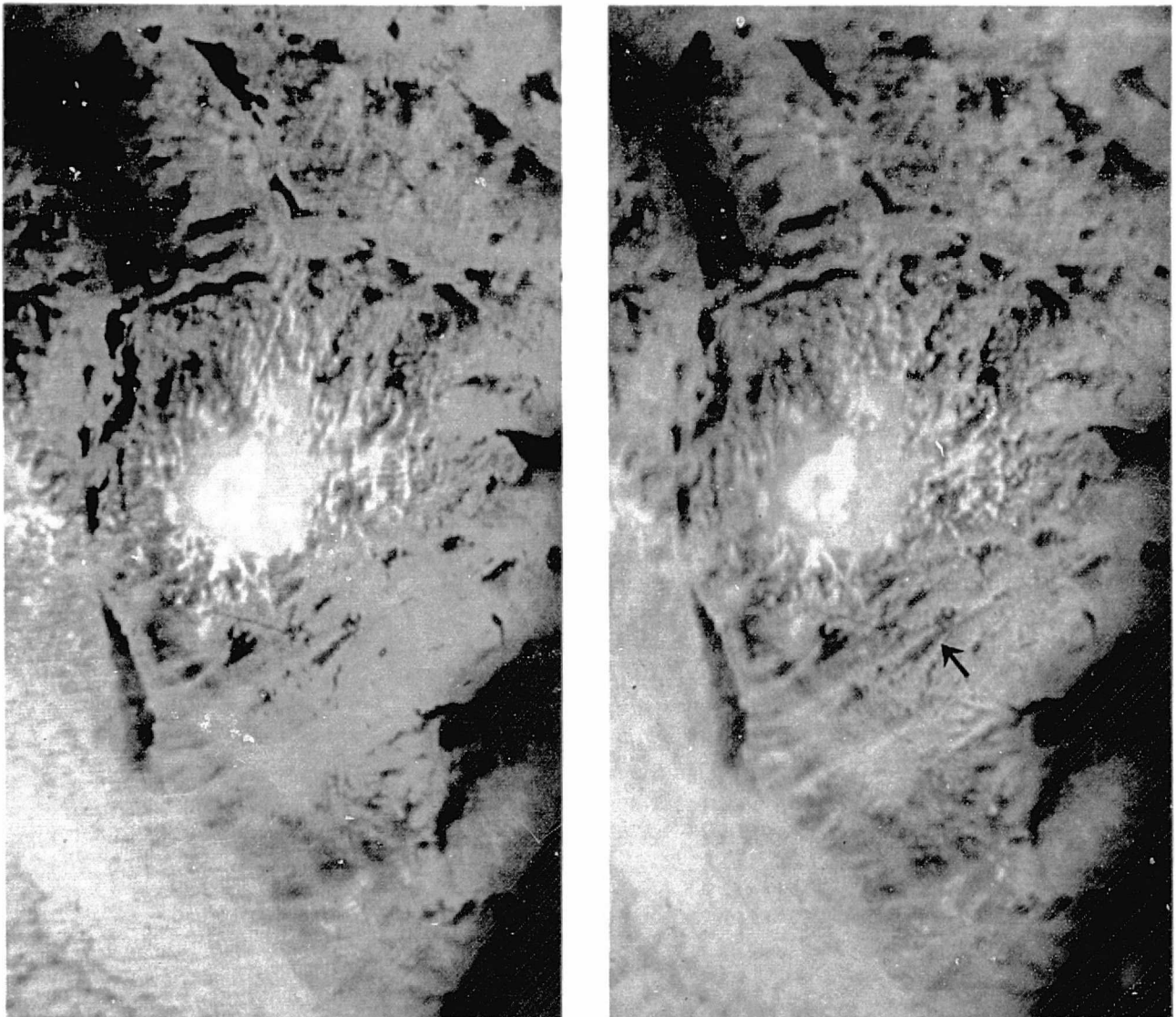


Fig. 16 On its sixth day of operation, LANDSAT-1 scanned Europe's northernmost glacier, the dome-shaped Seilandsjøkulen. (Part of image No. 1006-09481, taken on July 29, 1972. Approximate scale 1:50 000).

The transient snow line is clearly visible on the image. This illustration demonstrates various colour combinations of MSS 5, 6 and 7 (green, blue, red (left-hand picture) and red, blue, green (right-hand picture)). The last mentioned combination proved to be the best to emphasize the snow line, and it also revealed sediment-loaded streams and lakes, see arrow in the right-hand picture.

The height of the transient snow line can be easily determined from a contour map of the area.

nificantly improve results or help to produce them quicker, so we feel that the use of digital data is not justified in this particular application of LANDSAT data.

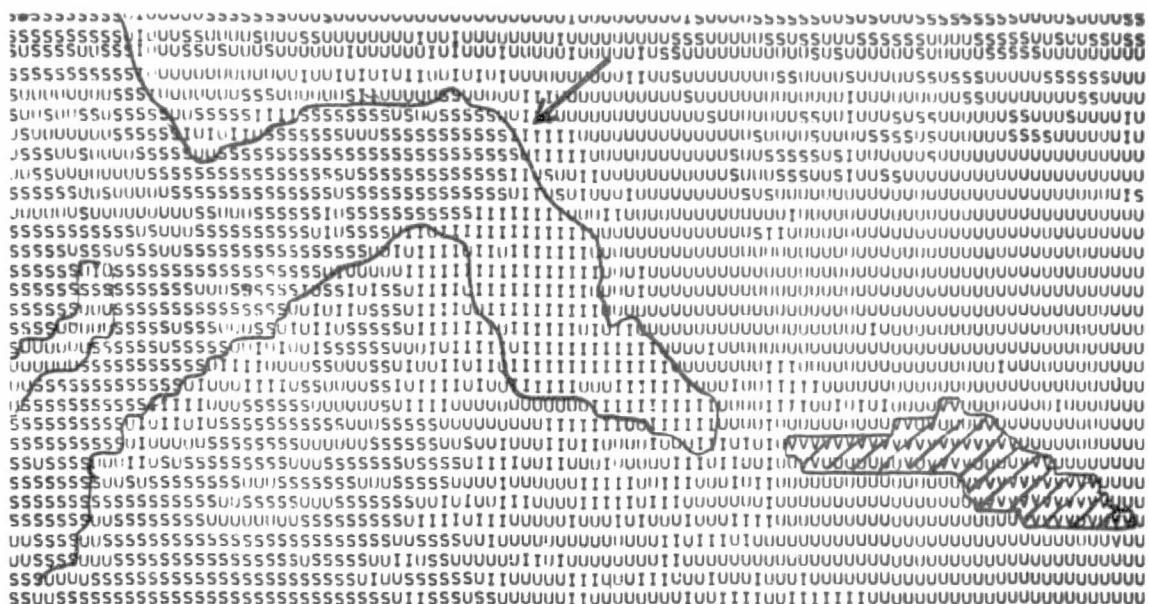


Fig. 17 Although the transient snow line normally can be seen directly on photographic enlargements of LANDSAT images, some experiments were made to map it from the digital data on CCT.

Here the snout of the glacier Nigardsbreen can be seen, I is ice, S is snow, and W is water. U stands for "unidentified material" - mainly rock. The transient snow line can be seen at a fairly low altitude (see arrow), because the image was taken early in the season, on June 24, 1973. There are also still some snow and ice patches on the valley sides at this early time, but they disappear during the summer, compare Fig. 14, which is taken near the end of the melt season.

Printout constructed from LANDSAT CCT 1336-10260.

Conclusions

Glacier mass balance investigations are of great interest for hydrological purposes. Particularly in the planning procedure of hydro-electric power stations it is vital to forecast expected amounts of water available for future installations. If existing statistics are based upon observations during years of negative glacier mass balances in the catchment, this figure might be too "optimistic" because the glaciers have, in the past, contributed significantly to water runoff, i.e. amounts of water that were not directly a result of precipitation.

Such errors in the statistics can be corrected if information of the glacier mass balance is collected for at least one or two glaciers in the catchment. It is obvious that these glaciers must be selected carefully to give representative results. The field work connected with glacier mass balance studies is expensive and requires more manpower than most other kind of field work in hydrology.

It exists a linear correlation between the glacier's mass balance and the height of the transient snowline at the end of the melt season. Consequently, one could observe the height of the transient snowline at the end of the summer, and this would give useful information to determine the mass balance for that glacier. A condition is, however, that mass balance investigations and snow line observations have been made for a number of years in the area, to establish the above mentioned linear relationship.

LANDSAT images show the position of the transient snow line with sufficient accuracy and the resolution in the 70 mm film material is good enough for most glaciers in Norway. Images acquired at the end of the summer season will, therefore, give sufficient information to determine the height of the transient snow line provided good topographic maps are available. Hence, the mass balance for that glacier can be found at a low cost for that year. Experiments have shown that the method is realistic and can be used for hydrological purposes, but the main problem is the availability of data at the right time of the year. Cloud cover is also, of course, a limiting factor.

However, if satellite passages were more frequent, we feel that it would be possible to obtain at least one useful image of the glaciers under study near the right time in the fall. Thus, one could extract the necessary data to complete the task.

Cost/benefit studies have shown that for the Nigardsbreen outlet glacier one would save annual amounts in the order of \$ 10 000 if such images were available on an operational basis. This figure is calculated on the basis of necessary glaciological field work to be done annually in order to monitor the net mass balance of that glacier - for other glaciers it is likely that the cost/benefit will be different. In any case it will be necessary to perform conventional mass balance studies for a series of years to obtain a curve of the type shown in Fig. 13, before the use of satellite data can replace field work.

DIGITAL METHODS

Each scan line recorded on magnetic tape (CCT) contains between 3000 and 3450 "point" readings. Each line is 185 km long on the ground and contains, for example, 3240 bytes which will give $185/3240 = 57$ m/byte. Consequently, this means that one reading is made, at an average, for every 57 m along the scan line. This is, however, only a theoretical value because the area "seen" by the sensor is slightly larger and readings along scan lines are thus overlap-



Fig. 18 Oblique air photograph of the test area Kjela, taken on July 8, 1975. Typical landmarks are the highway and islands in the lake. These are used when the line printouts are adjusted to topographic maps of the area, compare Fig.

ping each other, somewhat more in the middle and somewhat less towards the ends of the scan line.

An image consist of 2340 scan lines, which gives $185/2340 = 79$ m/line. This means that the centre of the scan lines are located 79 m apart on the ground.

The word "byte" can in this connection be replaced by the word "pixel" (picture element). By simple mathematics we have then:

Number of scan lines per image		2 340
Number of pixels per scan line	approx.	3 240
Number of pixels per image	"	7 581 600
Area per image	185 km x 185 km	34 225 km ²
Area per pixel	approx.	4 500 m ²

This means that if the value 79 m is taken as the height of the pixel, its width will be $4500/79 =$ about 57 m.

However, for simplicity it is practical to assume that the pixel size is 80 m x 80 m on the ground, although the "view of sight" is circular or slightly elliptic, partly overlapping neighbouring pixels.

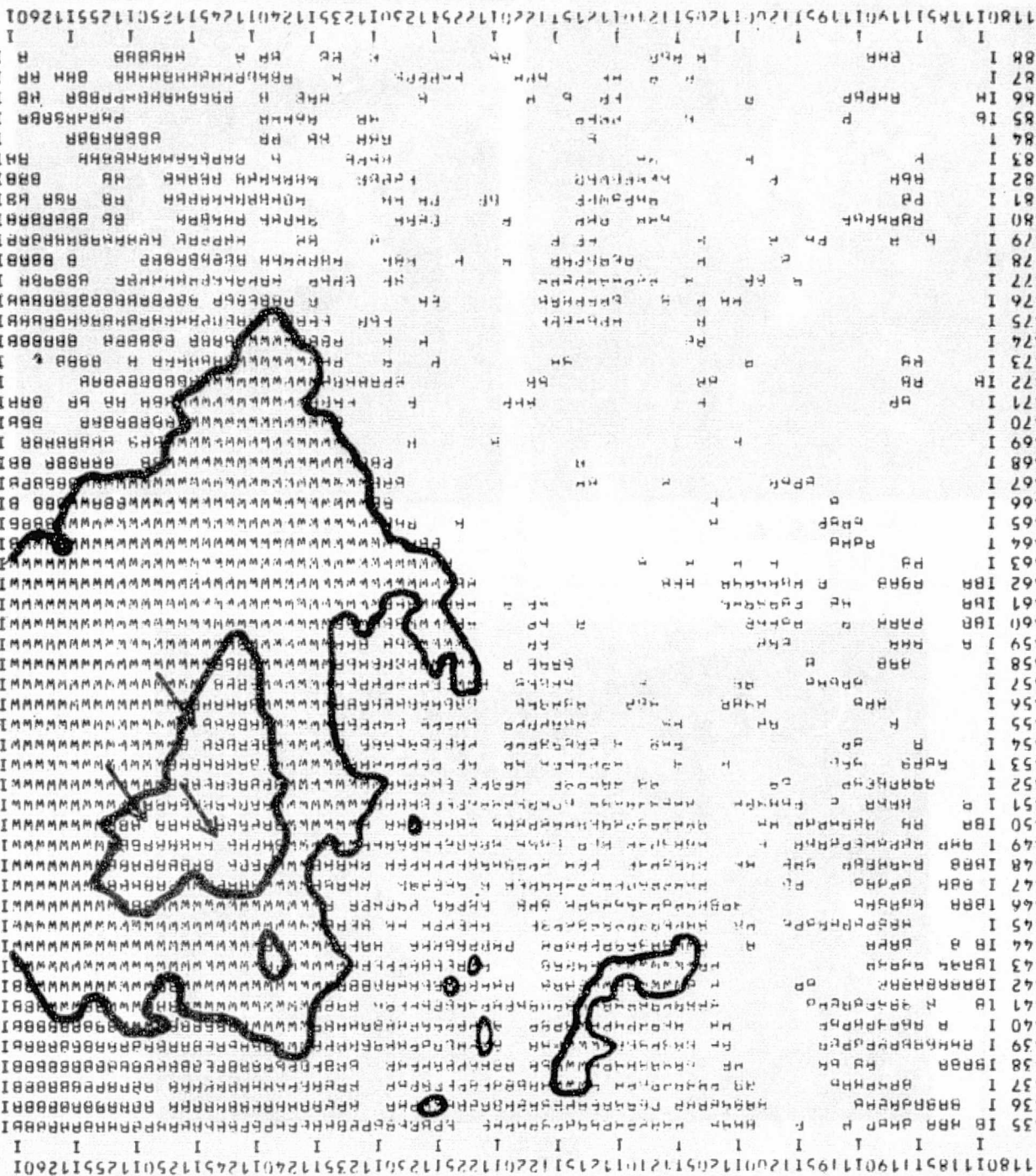
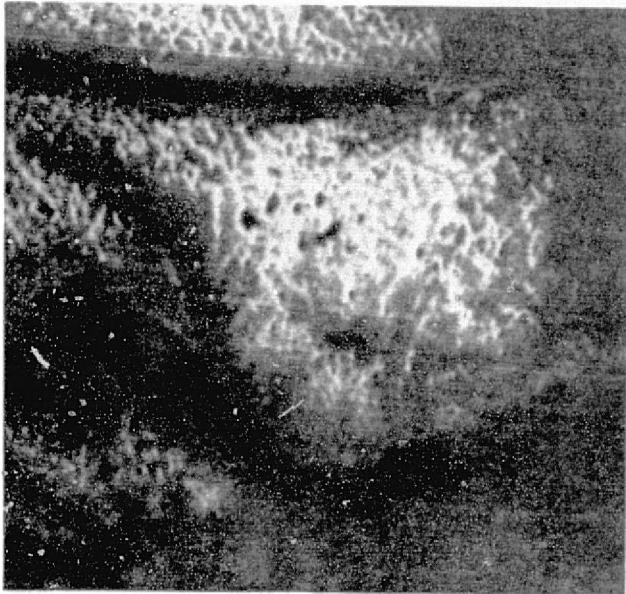


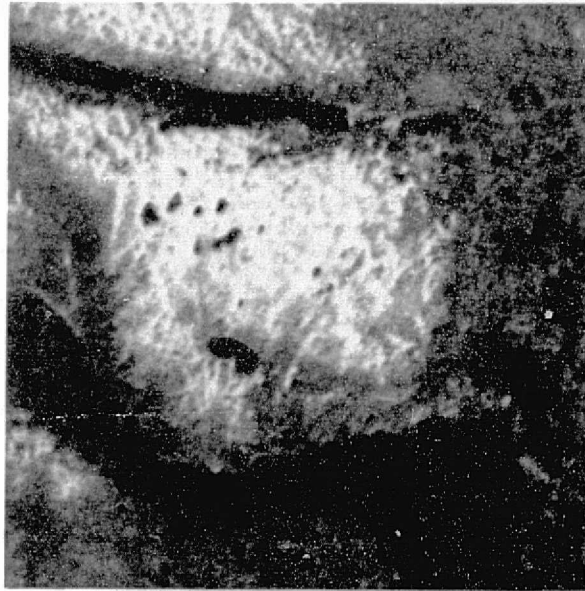
Fig. 19 Test area Kjela. A computer printout made from LANDSAT image No. 2168-10032 taken on July 9, 1975. The "Euclidean distance" method was used to classify the following three classes from MSS 5 and MSS 7 data:

W - water
B - bare ground
blank - wet snow

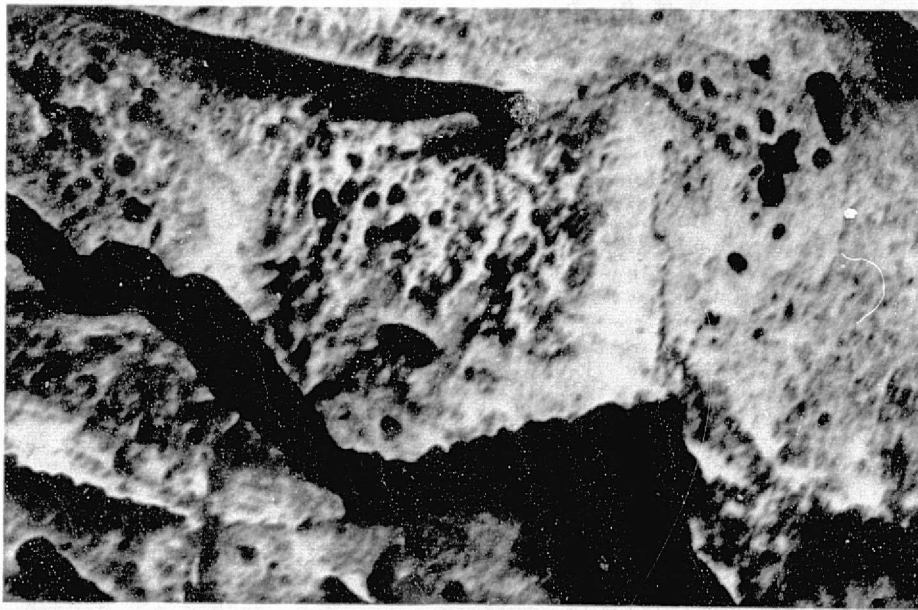
If this "computer map" is compared with the oblique air photograph shown in Fig. 18 one can see that there is a good correlation between snow patches on the photograph and blanks on the computer map. Note for example, the snow patch on the biggest island in the lake - it is represented by two blank pixels on the printout.



MSS 4



MSS 5



MSS 7

Fig. 20 An experiment to map snow cover on the same date (July 9, 1975) but from various MSS bands from the LANDSAT image 2168-10032. MSS 4 and 5 (upper pictures) show most snow on the ground. Areas of vegetation are generally dark and there is a poor contrast between snow-free land and water surfaces. The higher parts of the terrain have a light tone which is rock surfaces, grass or moss.

MSS 7 (lower picture) shows less snow - only the deepest snow in the highest parts of the area is shown as white areas whereas wet ground around the snow is relatively dark. The contrast between land and water bodies is high (compare Fig. 33 where MSS 7 was used to delineate water bodies). Birch trees are causing a relatively light tone due to their high reflectivity in the near-infrared part of the spectrum.

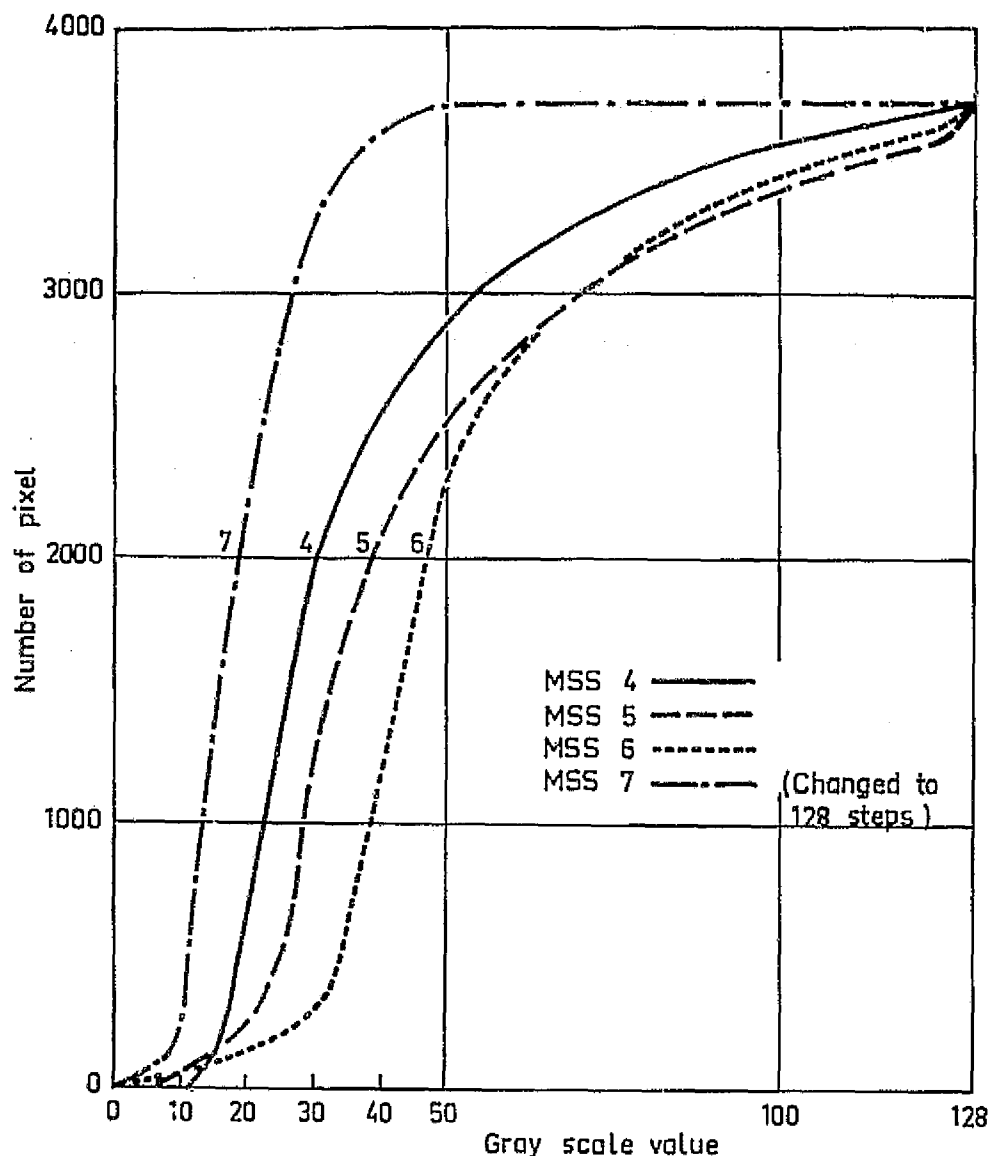


Fig. 21 This diagram is based upon part of the LANDSAT image No. 2168-10032. All pixels within the test area Totak were counted and cumulative diagrams plotted, so that the frequency of various bands are demonstrated.

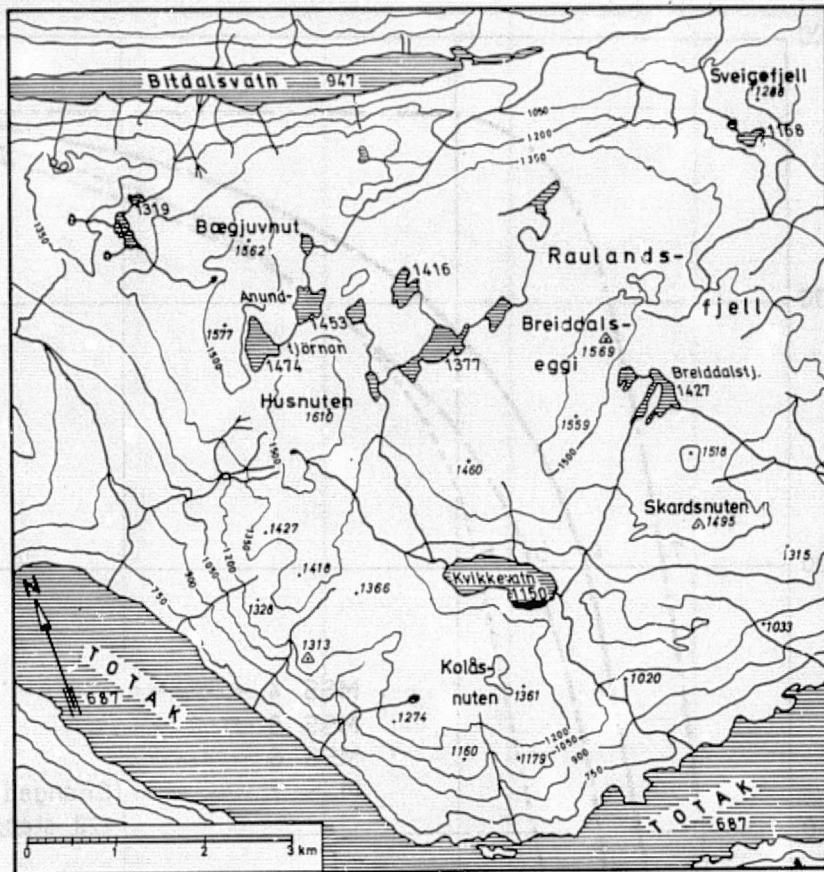
MSS 4 has the lowest value 10, most of the values are between level 10 and 50.

MSS 5 is similar to MSS 4 but starts at level 5.

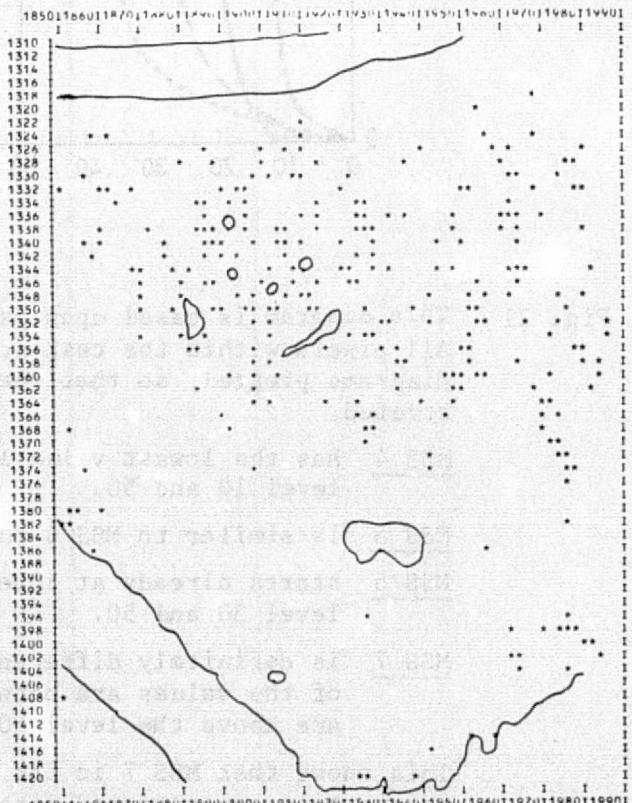
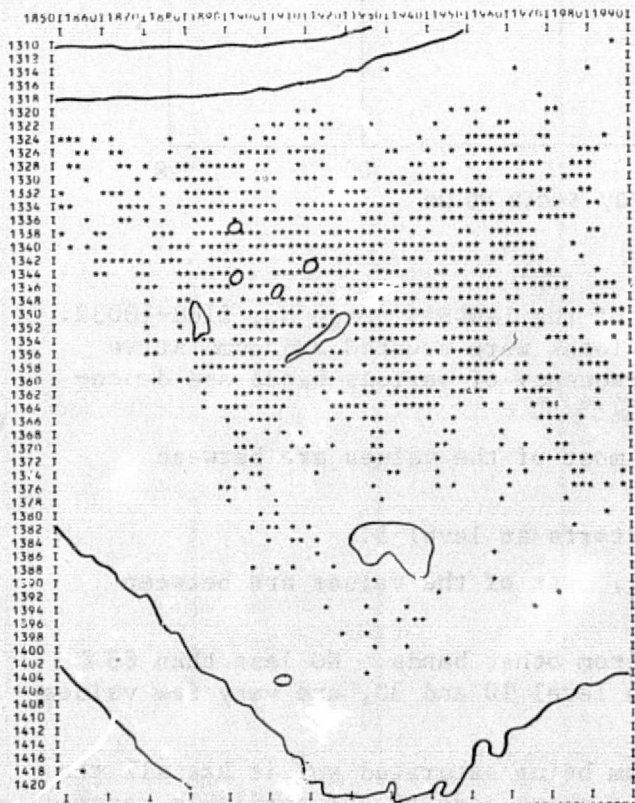
MSS 6 starts already at level 1, most of the values are between level 30 and 50.

MSS 7 is definitely different from other bands. No less than 83 % of the values are between level 10 and 30, and very few values are above the level 50.

This shows that MSS 7 is far from being saturated and it has all the information concentrated within a short part of the available range. MSS 4 and 5 have almost the same relative response.



a)



b)

c)

Fig. 22

To be able to determine what is actually the snow limit in the field, exact observations have to be made at the time of the LANDSAT overflight. For our test site Tokke which was overflown by LANDSAT on July 9, 1975 we have colour pictures obtained from low-flying aircrafts on July 8, 1975. It is simple to determine the exact location of patches of snow relative to easy identifiable objects on the ground (lakes, highways). It was by the help of this material possible to determine that it was a good agreement between the snow limit as determined by colour film and the LANDSAT MSS 5. The exact location of the limit was also observed on the ground and was the same as observed on the colour film. The same can be said about the MSS 4 which also was well correlated with the actual snow limit. The MSS 6 and MSS 7 recorded only part of the actual snow pack as snow.

If we compare the number of pixels values above the limits 34% (gray-scale value 44) for MSS 5 and 24% (gray-scale value 31) for MSS 7 we obtain the following result for the test area Totak:

MSS channel 5: 919 pixels

MSS channel 7: 278 pixels

and the ratio is: $\frac{919}{278} = 3.31$. This may be an index of snow ripening, but it has no practical interest for our purposes.

An unsupervised clustering analysis was made for a part of the test area, the lake Kvikkevatn. The signatures of the different classes are shown in Fig. 23 together with a summary and number of pixels in each group. The test area is shown in Fig. 22.

Fig. 22 The test area between the lake Totak (elevation 687 m a.s.l.) and the lake Bitdalsvatn (947 m a.s.l.). The highest point in the area is 1610 m a.s.l.

- a) A topographic map of the area.
- b) A CCT print-out showing the snow cover on July 9, 1975, based upon the band MSS 5, only. All pixels which are classified as snow are marked by an asterix. These areas, which have a brightness level between 44-128, were marked. A pixel count gave as result that 23% of the total drainage basin was snow-covered (919 pixels, each covering 0.451 km^2 gives a total snow-covered area of 414.5 km^2).
- c) This is a similar printout made from MSS 7 where all pixels with a brightness level more than 32 were marked by an asterix. Its total area amounted to 7% only. Note that the pixels in this case are located mainly in the higher parts of the basin.

a)

```

1368 T  X0000000000 000000001 W11XXXXXX001W0*I
1369 IX1 000x0000001 10000**0**01 11XXXXXX0x111*I
1370 I000XW11000000 A200000001 01 WW11X...XXXXX1 WX*I
1371 IXX*1 1WWX000W A0 1000*0100 11 .X.XXXXXX +*I
1372 I1X01100010X01 0 000**0 01 XX...XXXXX1W0+*I
1373 I1XXx000100x01 1W10000000*0 XXX00X0X.*X 0+*0I
1374 IW+XXXX000X100X111 1W 000*00 XXX00X0000XX++0 I
1375 I10X...XX*0001 W1001 10*0000001 *W XX***00***0 I
1376 IXX...XX1111X 0*X 1XX*X0001WWX1 WXX++0000000W I
1377 I0 X...XX...x1 1 .*X.*0XXXX11Y XXX*****200 I
1378 IXYx*x. ....x001 .....XXXXXXx1 XX++++++*0 0I
1379 IX XXX.... .XXX.....XX.XXX*. .XXX.++++*20 W I
1380 IX. .xX..... .XX. ....XX.+++++++01 1I
1381 IWx.X.....XX.....XX. ....XX. ....X.I
1382 I100++...X. ....2AAA22+ .....++X+. ....2+... ..I
1383 I1X...++2A.....AAA222.....XX. ....++X...I
1384 IWOX*XOX+A.....A22+. .XXX*++X++++*1X...I
1385 I1 +XX.+2.....A+. .++++++.*XX...I
1386 I W1+x+++++A.....AAAAA.....2. ....++X ...I
1387 IX0**1XX+x1*2AA22222+ 2-----A2++++++X 1+.I
1388 I0001WW+XXx+++++*0XX2-----2+10++++0+++ .+++I
1389 I0***W W10++++ 0+++ 022AAA22*01++++++00+1 .+++I
1390 I*X1W1 0* 2+ +2*XX+++++2*0 1XX++++XX +2+I

```

UN-NORMALIZED CATEGORY SPECIFICATIONS

b)

CHANNELS-	4	5	6	7
1 .	18.41	22.53	43.59	21.99
2 X	20.78	26.08	41.95	20.20
3 +	17.21	20.75	34.83	16.76
4 0	25.45	30.86	38.04	16.27
5 -	10.92	8.67	5.90	0.73
6 A	12.18	11.09	10.59	2.73
7 *	21.09	24.55	36.18	16.91
8 W	37.56	46.22	56.00	22.67
9 1	28.87	37.25	46.75	20.12
10 2	13.00	13.00	20.50	9.00

SUMMARY

c)

NUMBER	SYMBOL	LIMIT	COUNT	PER CENT
1	.	8.92	154.	14.
2	X	8.28	174.	15.
3	+	9.70	146.	13.
4	0	8.55	170.	15.
5	-	6.32	70.	6.
6	A	9.67	24.	2.
7	*	9.36	96.	9.
8	W	4.81	28.	2.
9	1	6.75	80.	7.
10	2	27.61	34.	3.
11		0.0	151.	13.

TOTAL COUNT 1127

Fig. 23

We definitely feel at this stage that it would be wise for a beginner to start snow mapping with simple methods which he can understand relatively easily and without prior knowledge to complicated techniques.

We feel that there are three main reasons to disregard a digital computer-based system for snow cover mapping from LANDSAT imagery at this stage:

1. It takes more time to get CCT-tape than film chips. The use of CCT requires that the user has computer programs available and is able to use them - or is able to get somebody to do it for him. The initial cost is high for digital work.
2. When working digitally it is difficult to separate clouds and adjust for this disturbance. We do not consider this to be a major problem when working directly from paper prints. The owner of the power plant (the hydrologist) has his local knowledge of the shape of every mountain in the catchment area and he will notice any deviations due to clouds. If the image is partly covered by clouds, he will probably not be able to measure the total area of snow cover, but he will be able to use some old imagery, compare, and still be able to get useful information.

Fig. 23 Test area Totak (southern Norway).

- a) Computer printout from a classification made from LANDSAT image No. 2168-10032-obtained on July 9, 1975. The "Euclidean Distance" method was used to cluster 10 classes from all the bands MSS 4, 5, 6, and 7. The lake Kvikkevatn is outlined. Approximate scale is 1 : 26 000.

The different classes are:

1 .	Vegetation	7 *	Vegetation
2 X	Vegetation	8 W	Snow
3 +	Vegetation	9 1	Snow
4 0	Vegetation	10 2	Vegetation
5 -	Water	11	Unclassified
6 A	Water		

- b) This table illustrates the signature of different classes to give the reader some idea of the spectral response of various bands. Typical is the low band 5 and 7 response for water bodies (printout code A and -). Vegetation has a relatively low band 5 response. Printout code: see above. Snow and ice will have a typical high band 5 response, so it is sufficient to use this band alone for snow mapping.
- c) This table is a pixel count for the basin, showing the size (radius) of each single cluster ("LIMIT"), the total number of pixels within each class on the printout ("COUNT") and their percentage within the total number of counted pixels which is 1127 in this case.

3. The main advantage of computer-aided snow mapping is the possibility of getting a very accurate value for the snow-covered area. This is fine if all snow surfaces were surrounded by bare ground within the catchment area. However, most often the catchment limits partly follow mountain ridges and thus go through surfaces of solid snow cover. Lakes are also often ice covered (June) and this may make it difficult to locate pixels.

PROBLEMS WITH FOREST, CLOUD COVER, ETC

It was found that it is very difficult to determine accurately the snowline elevation or the extent of the snow cover if parts of the area are forested. Therefore, the method is best suited for high mountain areas.

With little snow on the ground it may be difficult to see the difference between old, deep snow and a thin layer of new snow. This may be clarified by the use of meteorological data. The sun angle may also disturb the interpretation, due to unwanted effects of shadows.

Cloud formation is another disturbing factor because it appears in the imagery with the same grey tones as the snow cover. Separation of clouds from snow and ice can be done visually due to the special shape of clouds. An automatic differentiation does not exist today and will probably be difficult to develop with the given wavelengths available.

Meteorological observations for the station named Nerdal show that the chance is much less than 5 per cent that we obtain a cloud-free image on a given pass. See Fig. 24.

A test was made to determine how much of the snow cover on the mountain plateau Hardangervidda in South-western Norway was in the shade when the whole area was covered with snow. The image 2024-10034 obtained on Feb. 15, 1975 (Fig. 2), with a sun elevation of 14 degrees showed that less than five percent of the area was covered by shadows. The snow melt from this area starts approximately in the middle of May each year, so the use of satellite data will be of most interest in June and July when the sun elevation has increased to 45 - 50 degrees. Thus, we do not consider shadows to be a problem in our work, unless we approach areas of more broken topography (which does exist in Norway, but not too extensively).

Experience from Skylab (Bartolucci, et.al. 1975) indicate that a separation of clouds can be made if wavelengths 1.55 - 1.75 μm or 2.10 - 2.35 μm are introduced.

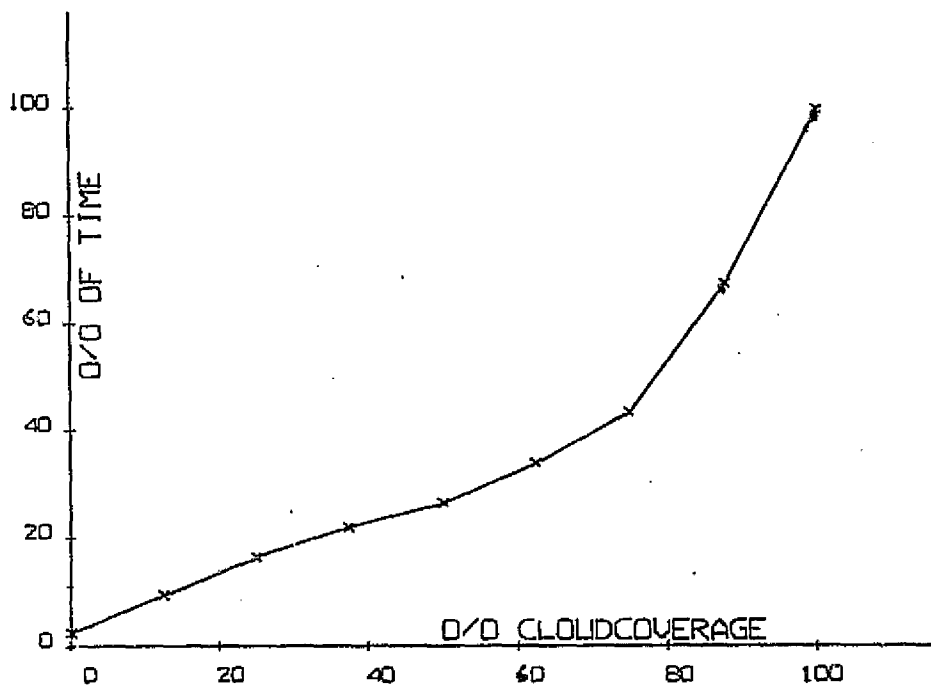


Fig. 24 Diagram showing the frequency of cloud cover. Less than 50% cloud cover occurs only during 25% of the time. 50% of the time the cloud cover was 80% or more. The data are plotted from observations from the Nerdal meteorological station (Røssåga) at 7 am during the period January through July, 1973.

Snow will then come out dark while the clouds come out light. Consequently, it can be concluded that a separation is possible if these wavelengths are added to the ones in use today. For LANDSAT this will remain a problem when using automatic classification due to the limited bandwidth 0.5 - 1.1 μm .

SNOW MEASUREMENTS USING GAMMA RADIATION

The State Power Board is every year mapping snow cover in its catchment areas in Southern Norway using the gamma radiation method. A small fixed-wing aircraft with a detector and recording instruments are flown at an elevation of approx. 200 metres and the natural gamma radiation is recorded. The observed radiation is an inverse function of the water content of the snow. The basic parameters used in the calculation are obtained during a similar flight under snow-free conditions in the fall. Moisture in the soil will influence on the radiation, so all flight lines are planned to exclude areas with lakes or swamps. The same lines are flown in

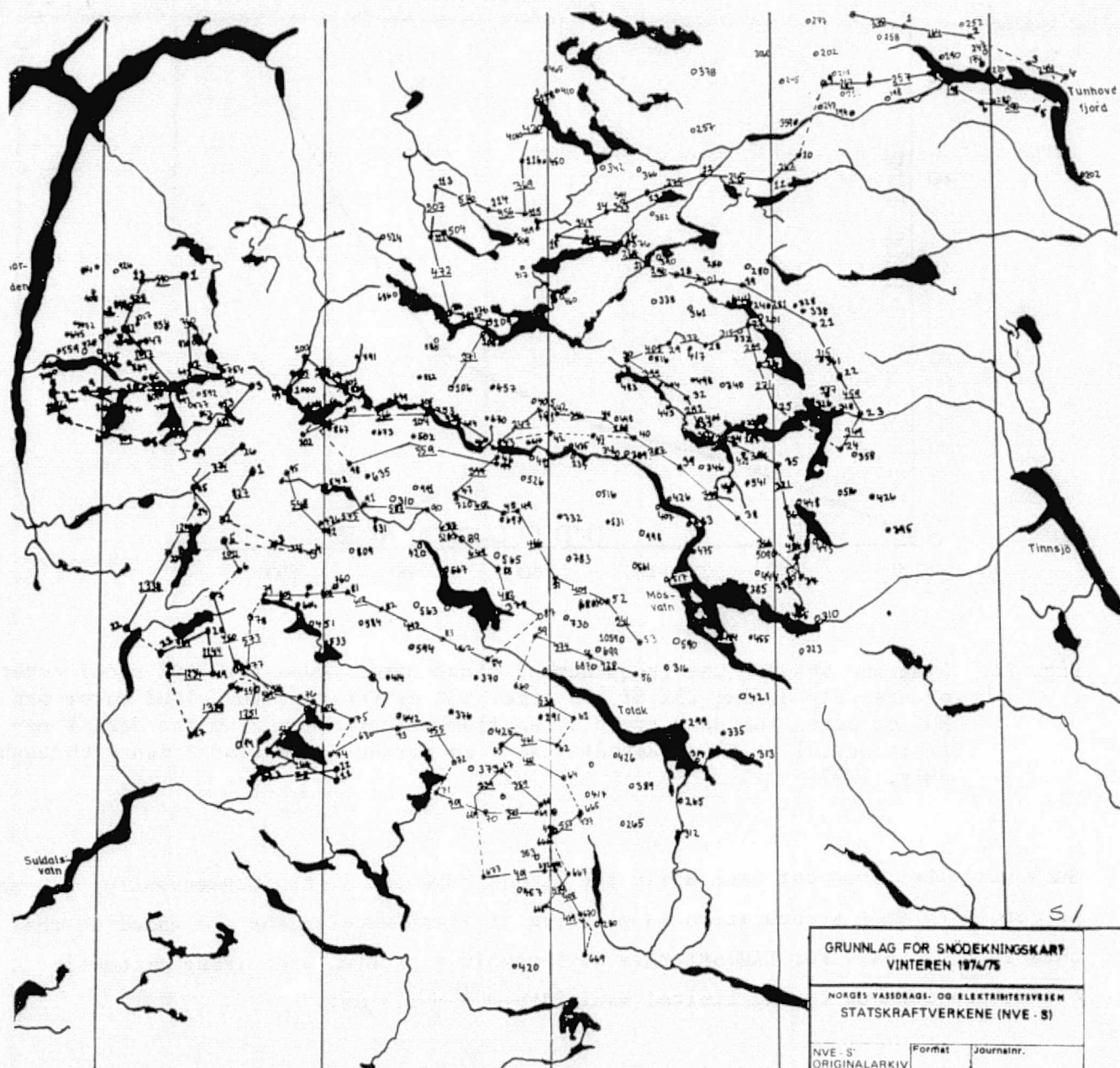


Fig. 25 Base data for the snow accumulation map shown in Fig. 26. Single numbers indicate ground observations (snow courses). Lines indicate flight lines for gamma radiation measurements. The mean water equivalent found by this method is plotted for each section of the flight lines. All figures are in mm of water equivalent.

February and in April every year. The results are available shortly after each flight by the use of computers.

We have found that certain results in some areas are incorrect, but by conventional methods it was not possible to make appropriate corrections unless the whole area was reflighted, and this is rather expensive.



Fig. 27 Image 1332-10015, MSS-5, contoured at gray-scale level 6 and 10 by the use of Agfacontour Professional film. Level 10 gives the "snow-line" and level 6 delineates the thickest snow cover within snow-covered areas.

plotted in right positions, and the information was transferred to clear acetate. This overlay was placed on the imagery obtained in June and July. The MSS 5 was used when the snow cover was patchy and MSS 7 when the snow cover was continuous. This gave us an impression of snow depth, and we felt that the method works well. We have found a good relationship between water equivalents obtained by ground surveys in April and the areas with remaining snow in the summer. It may be possible

with some experience to get a feeling for the actual water equivalent in April within various areas just by looking at the imagery and having some point measurements on the ground.

The gamma surveys are flown in short straight lines about 5 - 10 kilometres apart, and the lines are often laid out in a zig-zag pattern. For each such line a value for accumulated radiation is recorded and the water equivalent for the course is computed. The snow courses (i.e. the short flight lines) were plotted on clear acetate and placed upon the imagery together with all other available information. When all this information was compared, it was a simple task to identify unreliable snow courses. See Fig. 25

When this project started, all snow courses (flight lines) were planned on topographic maps according to certain criteria. By the study of recent material it became clear that it was important to locate all courses in areas of homogeneous conditions. To start in a thick snow cover and end on bare ground proved to give unreliable results.

When the "gamma program" started in 1971, we had foreseen that something like this might happen and had included more snow courses than we felt necessary at that time. The number of snow courses is now reduced, and we feel that each of them represents a part of the total catchment area, and is thus given a certain weight. Such a system is now established, and the method will be used for the planned work in 1977. We feel that this use of LANDSAT imagery increases the value of the rest of our snow survey program.

WORK WITH AGFACONTOUR FILM

Some work has been done using Agfacontour film to emphasize the snow cover (Ødegaard, 1974). 70 mm positive film chips were contact printed on Agfacontour Professional film with yellow filters separating the grey tones of the film. It was possible to separate the level 10 (counted on the gray scale, starting from the left). When this Agfacontour film was enlarged on photographic paper, it gave a sharp, equidensity contour line around the snow-covered area and defined its boundary. The area of all snow patches were measured by a planimeter.

This method can be used for many purposes and especially for enhancement and "stretching" of imagery. The process takes some time but can be helpful if only simple, cheap equipment is available. The method has been used with good results to enhance the whole image, or part of it, for later use in an add-col-viewer. It can also be used in combination with the 3M product "Color Key".

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NOAA VHRR IMAGES

In addition to LANDSAT images, received from the EROS Data Center, some NOAA data were used as a supplement. However, three major problems were encountered in this work:

1. Overhead passes were not easily obtainable from the tracking station in Tromsø, Northern Norway, for local technical reasons.
2. The Tromsø station was unable to provide digital data.
3. Analog data, although photographically enlarged, gives normally a too coarse pic-

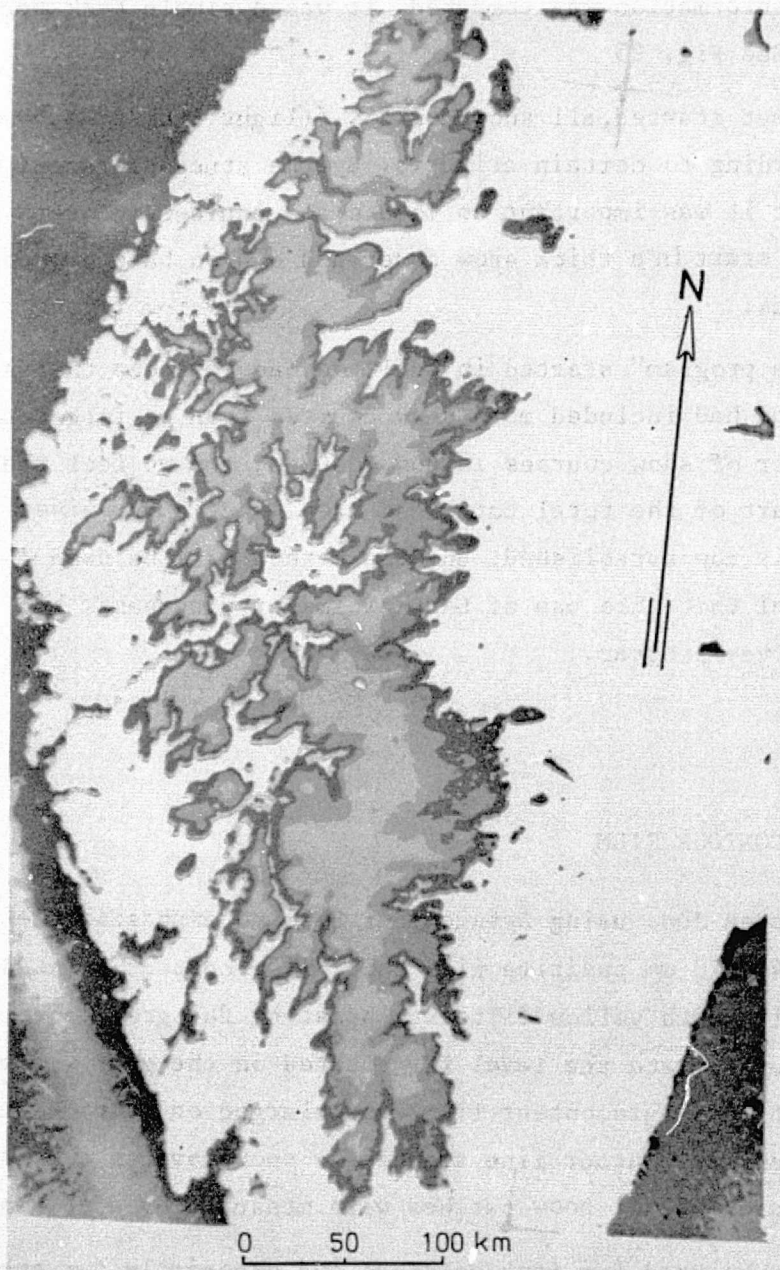


Fig. 28 Experiments were made to use NOAA-VHRR IR-images to indicate snow-covered areas in Southern Norway. The image was density-sliced by photographic methods, and it is anticipated that the various grey shades indicate various snow temperatures during the melt period. The image was taken on May 18, 1974.

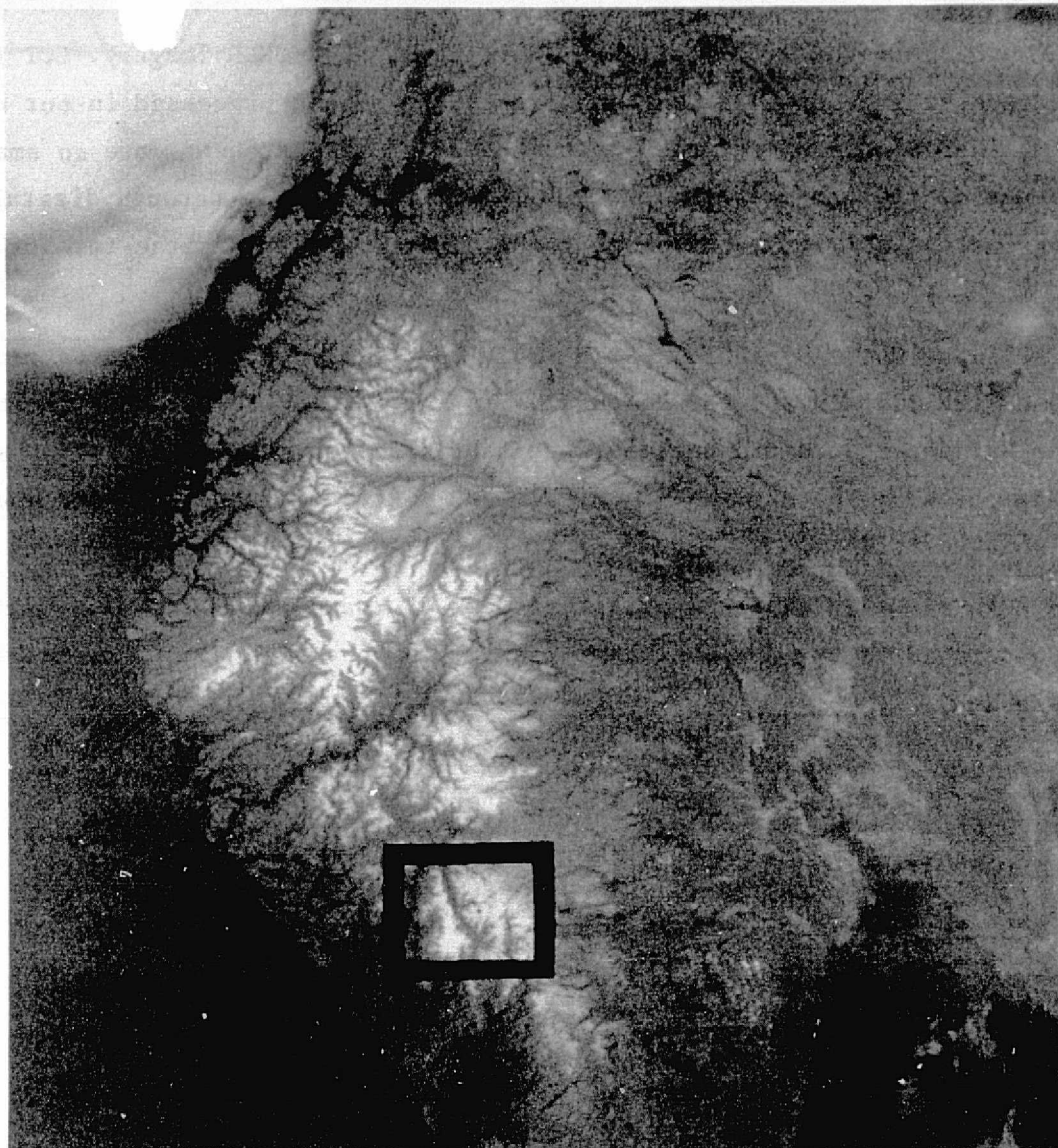


Fig. 29 NOAA-4-VHRR-VIS image covering the Southern part of Norway obtained on pass 3302 (August 6, 1975). The test area is indicated by a heavy line. See next page.

ture of snow conditions in Norwegian watersheds, because most of these basins are relatively small. Consequently, it is highly desirable to work with digital data.

The NOAA images can be obtained almost every day, a fact which is most important in Scandinavia, where complete or partly cloud cover is very frequent. The pixel size in the NOAA data gives probably sufficient information for the purpose, except in very small watersheds.

Fig. 28 shows a fraction of a NOAA-VHRR image (IR) acquired over Norway on May 18, 1974. This picture was processed via Agfacontour film to emphasize snow-covered areas. These areas seem to consist of cold snow surfaces in the highest elevations and less cold snow in the lower parts of the landscape.

ORIGINAL PAGE -
OF POOR QUALITY

We have some experience with digital processing of NOAA-VHRR imagery. CCT recorded at the receiving station in Lannion, France, have been processed in our computer to make snow maps of the Hardangervidda area. The catchments are so small (see table on page 9) that the resolution (900 x 900 m) available through digital processing must be utilized, the photographic images are too coarse for our purposes.

The LANDSAT image No. 2187-10084, MSS 5 (July 28, 1975) has been used as ground truth. (See Fig. 30). On the left hand side is the glacier Folgefonni, in the middle the Hardangerfjord and on the right hand side the western part of the Hardangervidda plateau. The snow had partly melted so that only the highest mountains have any snow left.

Data from NOAA-VHRR-VIS obtained on August 6, 1975 (pass No. 3302), i.e. nine days later, were printed on the computer line printer for the same area. The following code was used:

W	- water
blank	- bare soil, water
.	- continuous snow cover
1,2,3 etc.	- pixel areas covered by approximate snow cover of 10,20,30 etc. per cent.

The NOAA-VIS sensor (0.5 - 0.6 μm) is not suited for mapping water surfaces and it was thus impossible to obtain the fjord outline correctly by using the visible band.

The continuous snow surface came out clearly and there seems to be a lot of information about the snow surface in the data. The lowest reflection value of snow was 129 units and the highest 229 units on the grey-scale (which has, in total, 255 steps). This indicates that differences in reflectance from snow occupied 100 grey-scale steps, which is 39 per cent of the whole range.

The only corrections made by us were to adjust values within each scan line according to the target values.

Fig. 30 The upper picture is a part of the LANDSAT-2 image No. 2187-10084 obtained on July 28, 1975, covering the test area.

The lower illustration is the computer printout for the same area, acquired by NOAA-4-VHRR-VIS on pass 3302 (Aug. 6, 1975).

W and blank	- water and soil surfaces
.	- complete snow cover
1,2,3 etc.	- pixel area on the ground covered by 10, 20, 30 etc. per cent snow cover.)

ORIGINAL
OF 1000 COPIES

[illegible]

Fig. 30

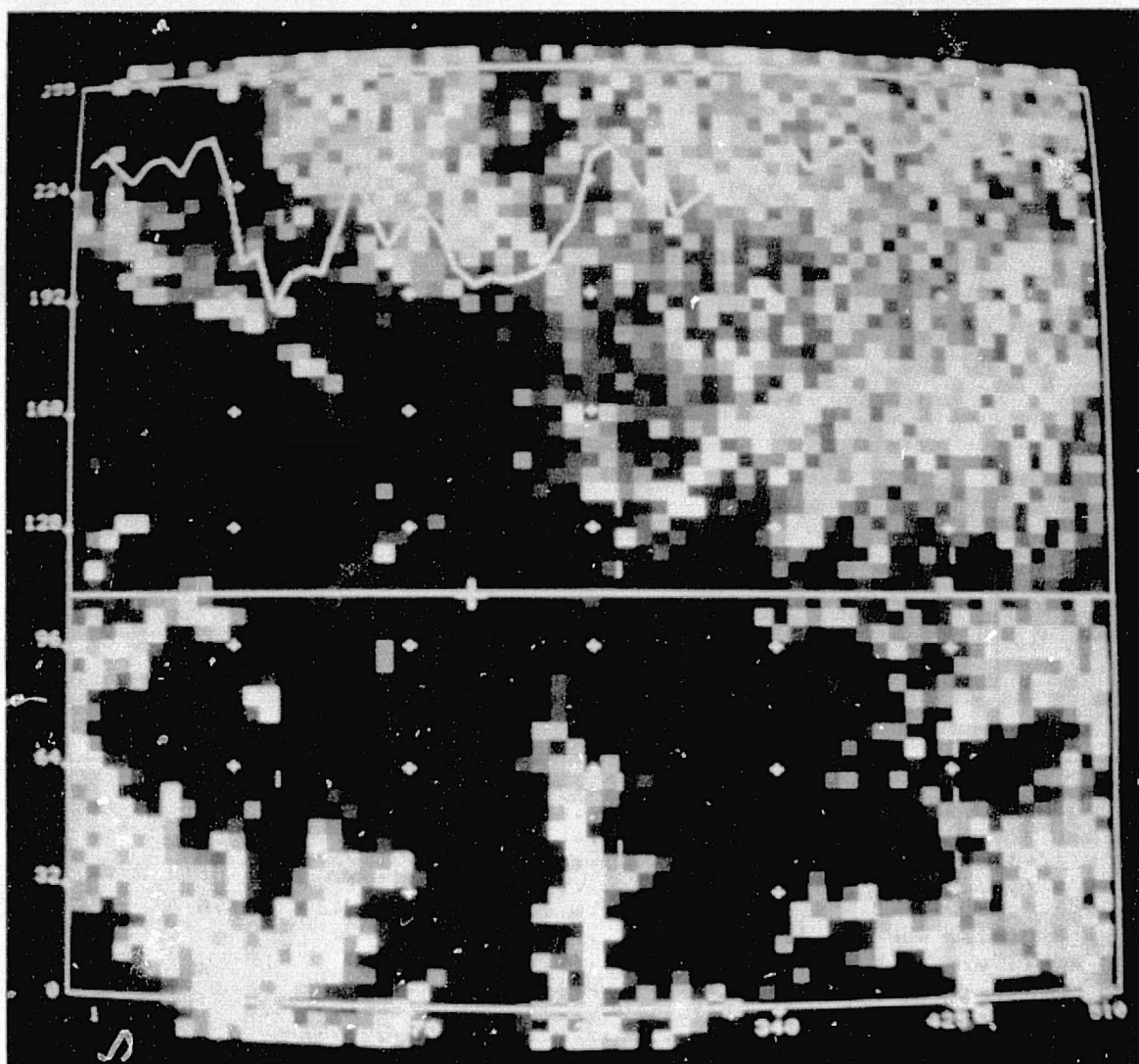


Fig. 31 The right hand part of the test area, generated from NOAA data; each original pixel is shown as a square on the IBM-ERMAN terminal in Madrid, Spain. Dark areas are snow. The intensity profile along the horizontal center line is shown as a curve in the upper part of the illustration. The grey-scale values range in this case from 192 to 220 for complete snow cover, between 221 and 229 for partial snow cover.

Concerning the practical, operational use of NOAA-data, we feel that a simple classification of an 1 x 1 km area as being either snow free or snow covered is a result which is not good enough when working with small areas. To solve this problem we might consider a square on the ground, 1 x 1 km in size, covered by dark soil and some small bushes which is normal for our high-mountain basins. If this area is gradually covered by 1/10, 1/5 etc. of snow, the re-

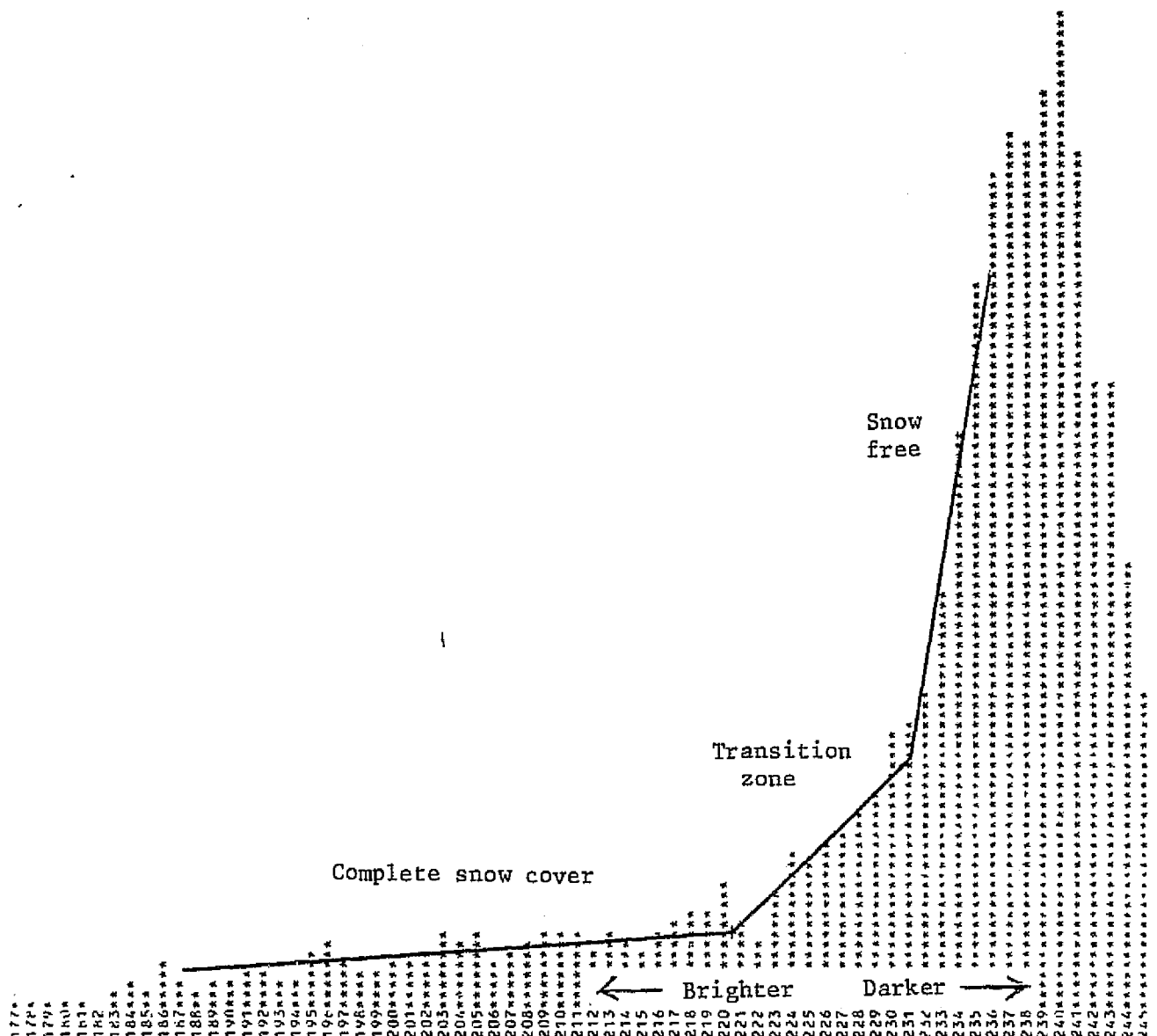


Fig. 32 Part of a frequency diagram (histogram) representing the grey-scale values from about 180 to 245 based upon the NOAA image shown in Fig. 29. Pixel brightness below the grey-scale value of 220 indicates that the soil is completely covered with snow, whereas values above 230 indicate that the soil is entirely snowfree. Between these values there is a transition zone with partly snow-covered ground. On similar NOAA recordings from a later date, the grey-scale values may be slightly different, but the shape of the frequency diagram will be the same under varying snow conditions, and this makes it possible to locate the transition zone (concerning grey-scale values) between snow and bare soil. A histogram as shown in this illustration is, therefore, one of the first things to do, in order to select suitable limits to be set for the production of a printout showing snow cover (compare Fig. 30).

Note that a high grey-scale value means darker areas on the ground.

reflectance from the area will also increase up to a value which, finally, corresponds to a complete snow cover. The reflectance of the area will, therefore,

change from that of soil to that of snow, according to how large a part of it is covered by white snow.

Such intermediate values are definitely very useful because they can be utilized to estimate the snow cover more precisely. We have, therefore, started to use the data to indicate per cent snow cover within each pixel and to print the results on a line-printer, see Fig. 30. Also data from the VHRR-IR-scanner can be used similarly.

The particular image which is referred to in this work (pass No. 3302), showed a displacement between identical points on the ground of approx. 7 km in the horizontal direction, as recorded in the two bands (VIS and IR).

COST-EFFECTIVE BENEFITS

LANDSAT data represent a source of information that cannot be produced in any other way today. We have made attempts to collect data about the snow cover by field measurements on the ground, but have not succeeded. The snowline elevation is not constant throughout the area but is a function of the prevailing winds during snow accumulation, exposure to wind, heating from the sun etc.

It is also difficult to move around on the snow surface when it is in the melting stage. The snow is then too weak to carry a ski-doo or similar over-snow vehicles. All necessary transport must take place during the night when the temperature drops below freezing and the snow surface becomes hard. Ground observations are, therefore, very difficult to carry out in the spring, i.e. at the time when we need the data.

We have been forced to use a small plane, and to take oblique pictures from low altitudes at certain points. This method cannot, however, cover the entire area, and this makes it difficult to analyse the material. The use of high altitude aircraft is expensive because they are not available in the area, and we have no suitable airports in the vicinity of our test fields.

LANDSAT data can be used at a very low cost. The snow extent can be easily mapped by an experienced analyst within a couple of hours by use of relatively simple instruments and inexpensive materials.

It is difficult to determine an economical value for space-acquired data during a certain period and hence the cost/benefit ratio. The annual production of electri-

city at the Røssåga power plant is 2470 GWh (2470 million kWh). If the use of space-acquired data could prevent 1 GWh from being spilled and instead routed through the power plants, this increased energy production has a first hand value of approx. 60.000,- N.kr. (\$ 10 000,-), but will have an even higher value for the country. In a given situation an amount of 10 GWh could be easily gained by a better knowledge of expected melt water inflow into the reservoir.

If a given volume of water is not taken out of the reservoir before it is completely filled and thus has to be routed over the spillway at a time when a high inflow to the reservoir occurs, this may lead to damage. The type of damage could be erosion and washing out of valuable soil, damage of highways and bridges, etc.

It is again difficult to put a value on this kind of effects, but it could easily reach an amount of 200.000,- N.kr. (\$ 35 000,-).

For our study area named Rana the production is approx. 4300 GWh/year, representing a first-hand sales value of approx. 30 million dollars per year. By the use of LANDSAT imagery we can obtain more information about the hydrological processes and in certain years it should be possible to increase the overall efficiency by 1 per cent. An increased production of 1 per cent will have a value of \$ 300 000,- per year.

The annual production of hydro-electric energy in Norway is approx. 80 000 GWh. A better knowledge of the hydrologic data would result in better production plans and a better use of the available water resources. If this can increase the production with only half of one percent, the value of the increased production would be in the order of 2.2 million dollars per year.

FUTURE PLANS

Work will continue on LANDSAT imagery to expand the file of historic data. Work will also be increased on the investigation of lower resolution NOAA-VHRR imagery with special emphasis on digital processing. We expect that sufficient data will soon be available to permit more detailed investigation of application to snow-covered areas for the benefit of hydrologic planning. It is expected that this will be a valuable new tool for hydrologists and decision makers in Norway.

For hydrology, particularly for surface water hydrology, satellite imagery is most useful. The entire drainage network, including lakes and streams larger than approximately 50 metres, is generally visible on LANDSAT images, due to the strong tonal contrast between water surfaces or lakebeds and surrounding areas. Water shows up sharp and black on MSS 7, whereas dry rivers or lakebeds and crust of silt or clay are highly reflective on MSS 4, 5 or 6. There is a sharp contrast between wet and dry areas on MSS 7. A comparison was made between the hydrological map (Fig. 34) and an enhanced print of band MSS 7 of an image acquired on June 20, 1973. This print

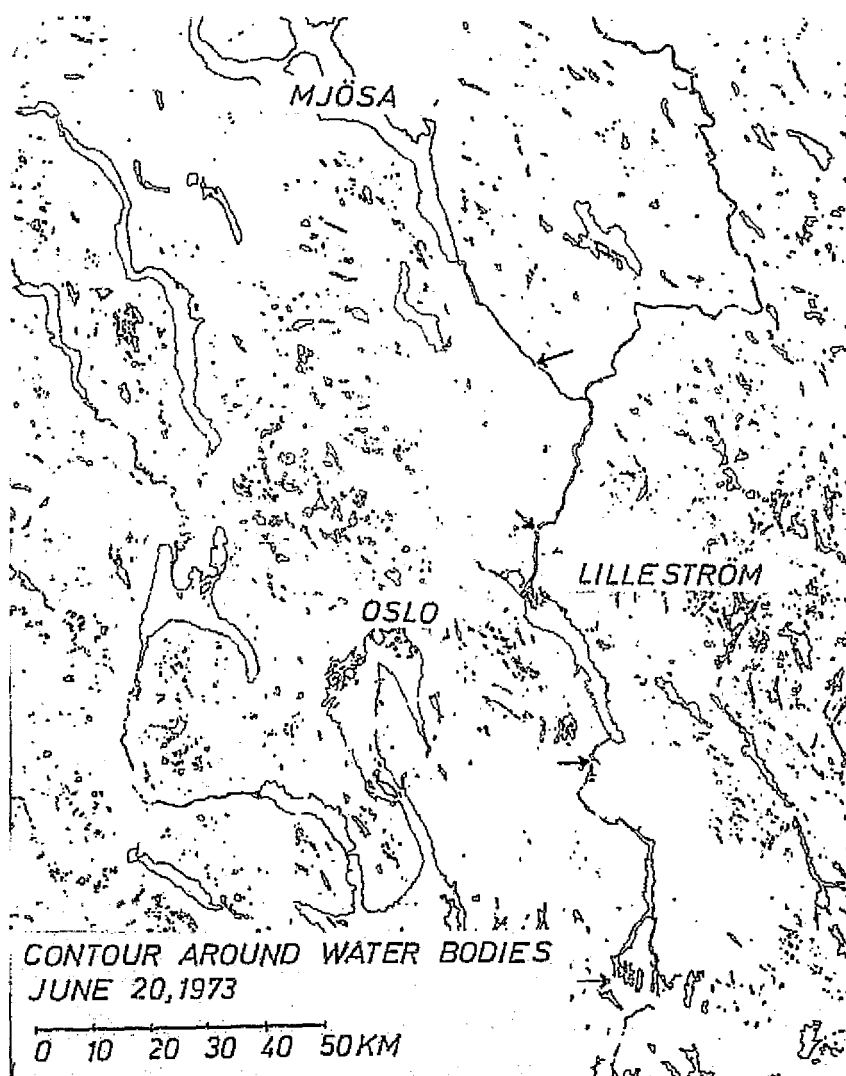


Fig. 33 A part of LANDSAT image 1332-10033, band MSS 7, was processed by Agfa-contour professional film. The grey-scale level 13 was emphasized and thus a thin black line surrounding all water bodies appeared clearly. The smallest rings indicate lakes approx. 200 m wide, small black points indicate lakes with a diameter about 100 m. The arrows are pointing at "breaks" in the water courses. In these cases the water is diverted through pipes or tunnels at hydro-electric power stations.

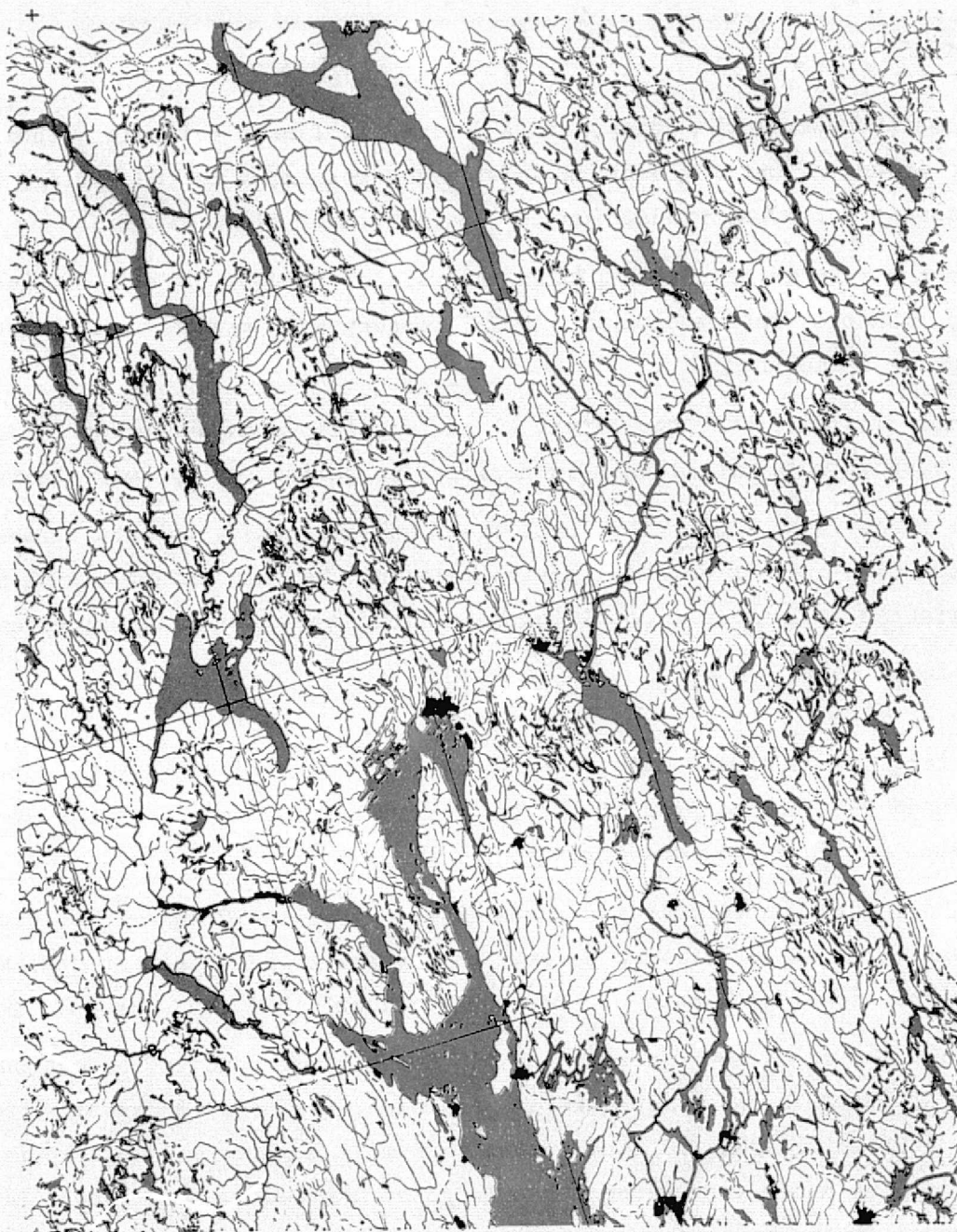


Fig. 34 Hydrologic map showing the same area as Fig. 33.

was made by using Agfa contour film and photographic methods. No ink has been used to prepare this map, which shows all significant rivers and lakes in South-eastern Norway.

It can be concluded that LANDSAT imagery is generally adequate without any ground truth information to map hydrological networks at the scale 1:1 000 000. Also enlargement to the FAO mapping scale of 1:250 000 is possible. Consequently, LANDSAT images could adequately replace the use of conventional aerial photography for this and similar purposes.

CONCLUSIONS

For the water power authorities, it is desired to find a reliable method to determine the amount of water stored as snow in the mountains in the spring. This is a vital concept for power production and prevention of flood damage.

Based on the results of the completed analysis of LANDSAT data it is concluded that the amount of information in LANDSAT imagery with practical application to snow mapping is substantial.

The results indicate that the extent of the mountain snow packs can be mapped from LANDSAT data in more detail than is depicted in aerial survey snow charts.

The cost in deriving snow extent maps from LANDSAT imagery is very reasonable in comparison with current data collection methods. The snow extent can be mapped by an experienced analyst in a couple of hours with very low material expences.

We have found that:

1. On large water sheds (more than 500 km^2) meteorological satellite data can be used for snow mapping if the parameters are determined by the use of observations from previous years.
2. LANDSAT data can be used for areas down to approx. $10\text{--}20 \text{ km}^2$ to accurately measure the extent of snow cover. There seems to be a definite relationship between the areal extent of snow cover (in km^2) and the subsequent runoff.
3. There also seems to be a relationship between area and subsequent runoff for different areas which make it possible to transfer information obtained for a group of areas to a new area. This will make it possible to use the method for a new area without knowledge of previous years. A condition is, however, that the areas are located in the same general type of climate and terrain and have the same runoff characteristics.
4. The relationship developed (see above) is quantitative and should make an important parameter as input to hydrologic runoff models. A great advantage is that the data are easy to obtain and easy to handle. The importance of such material increases with the increased cost of energy resources.

The use of a computer-aided approach to snow mapping requires expensive and complex equipment as compared to photo interpretation. There will also be a demand for computer programming and training of personel to implement such new methods. Today the demand for high precision and more information is not great enough to recommend such an investment for interpretation of LANDSAT data.

The natural gamma radiation as recorded from a low-flying aircraft has been used for snow mapping in Norway since 1971. It has been possible to increase the value of this program by comparing the readings made in February/April with the LANDSAT imagery obtained in June/July of the same year.

It is difficult to determine the economic value of space-acquired data for hydrological purposes in Norway. A better knowledge of the hydrologic conditions will, however, result in better production plans. An increased energy production of only one half per cent will have a great economic value.

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During the work we received—in addition to the images and magnetic tapes—a lot of information via various channels, one of them being the National Technical Information Service. This made it possible for us to keep up with similar work done in other parts of the world, a fact which is of the greatest value when studies and experiments are made in new fields of science and technology.

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