APPLICATION OF SATELLITE DATA FOR SNOW MAPPING IN NORWAY

H. A. Ødegaard[1], IBM, Oslo, Norway

T. Andersen and G. Ostrem, Norwegian Water Resources and Electricity Board, Oslo, Norway

ABSTRACT

The total volume of meltwater runoff from a given mountain watershed in the spring is related to the extent of snowcover. Data acquired from space are valuable if they are received by the user within a few days and if an operational use of the data is possible.

A diagram showing the relation between subsequent meltwater runoff and remaining snowcover has been established for several given catchment areas. It seems that the same curve can be used also for other high-mountain drainage basins. A curve of this type can be used directly for runoff forecasts as soon as snowmelt has started.

A method for use of digital NOAA/TIROS imagery for snow mapping is described.

INTRODUCTION

The Norwegian Water Resources and Electricity Board (NVE) annually produces 23,000 GWh or 30 percent of the electric energy in Norway and operates 45 hydroelectric power plants in the country. The rest of the electric power is produced in hydroelectric power plants owned by communities or private companies. No electricity is produced by thermal or nuclear methods. Therefore, snow surveys in high-mountain catchment areas are of vital concern to the management of power plants in Norway (Figure 1).

The winter production of power and the resulting draw-down of the reservoirs start in November. Ordinarily, snow surveys are made in the first week of February and the first week of April, before snowmelt starts. When the result of the first snow survey is available in the beginning of February, the first corrections in the production plans are made. Decisions are then made on how to distribute the total load between various power plants located in different parts of the country, relative to the size of their snow reservoir and ability to store the water during the following summer.

[1] H. A. Ødegaard was employed as senior hydrologist with the Norwegian Water Resources and Electricity Board (NVE) until October 1977, when he joined IBM.

Figure 1. Location Map

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 water volume. The plants with little snow will aim at a lower production in 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 transmission lines.

When the results of the April snow survey are 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 snow conditions. Some years a large amount of water may disappear due to evaporation or the filling up of the groundwater reservoir; other years the snow melts rapidly and only small losses are encountered. In this period, precipitation is recorded and the data are used to adjust the production plan. However, the main problem is the fact that very little information is available on snow conditions within the snow-covered areas for 3 months.

Implementation of thermal or nuclear energy into the present pure hydroelectric production system will increase electric energy prices and necessitate improvement of the daily management of the entire system. Accurate snow measurements will play an important role and contribute to increasing the overall efficiency of the power plants.

SNOWMELT – SNOW LINE

The winter snow covers the landscape almost down to sea level in most of the country. A snow line (border between covered and uncovered ground) does not exist in the catchment areas during the winter. Therefore, the area of snow cover cannot be estimated from imagery before the snowmelt has started and the snow line is well above the lowest point in the catchment basin. A "strand zone" then develops parallel to the shoreline of the reservoir.

The catchment area for all the major power plants is a rolling mountain terrain without or with a sparse forest cover.

RATE OF RUNOFF

After runoff has started, the snowcover remains close to 100 percent for some time. The volume of meltwater from the area during this first period varies according to the temperature pattern. The snowcover gradually decreases until the end of the snowmelt season. The daily amount of meltwater from the basin, or the basin snowmelt rate, starts declining before the summer temperature reaches its maximum value. The characteristic form of the snowcover depletion curve will be related to 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

For the Røssåga area, one of the largest basins in North Norway (Figure 2), the following expression (Figure 3) was found best to describe the observations:

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

S = percentage of snow cover

This expression will give the snowcover in percent for a given area t days after the reduction of the snow-covered area started, and may be used to estimate subsequent runoff.

RESULTS

Landsat data (Figures 4 and 5b) have been analyzed for a number of catchment areas. Aircraft data (Figure 5a) are used to provide detailed ground information of the area. The measured area of snowcover and the registered and corrected subsequent runoff were plotted separately for each test area. It was soon found, however, that data for different areas could be plotted advantageously on the same graph. A curve could be fitted through these points with relatively small deviations. The basins in the south had nearly the same runoff characteristics as those in the north, although the climate is entirely different.

Figure 2 Oblique photograph showing part of Lake Røssvatn for the power plant Røssåga *in* North Norway. *This picture is typical of most mountain drain-*age basins in Norway. More snow remains at higher elevations, where the snowcover is almost continuous. There is obviously no clearcut snowline.

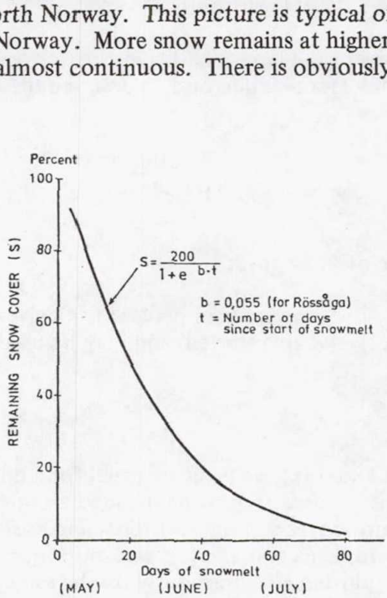
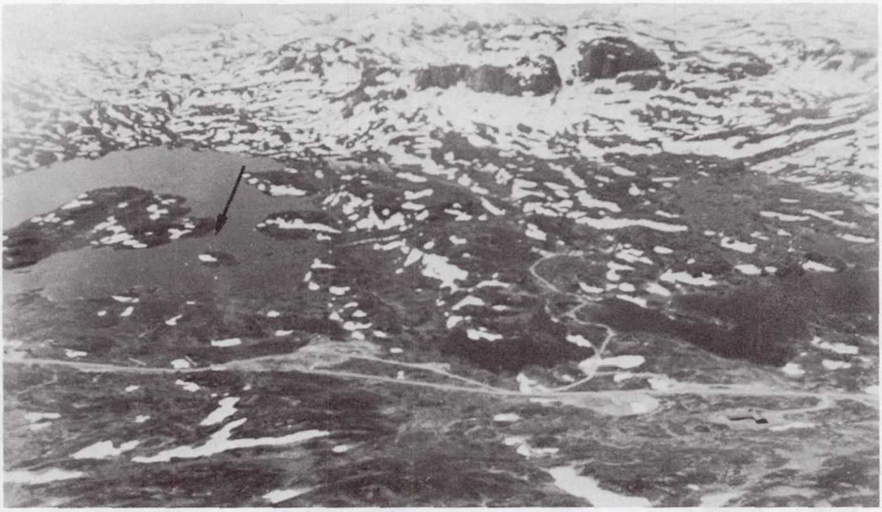


Figure 3 The diagram shows the typical decrease in snowcover, given in percent of the total catchment area, for the Røssåga drainage basin in northern Norway. The snow starts to melt in May. The snow-covered area decreases rapidly during late May and early June. In July there is a slower decrease in snow-covered area, possibly due to heavy snow accumulation in snow banks or patches of heavy snow caused by wind drift during the winter. There is almost no snow left in the area at the beginning of August.

Figure 4 The Landsat image 2168-10032 MSS 5, obtained July 9, 1975, shows the mountain plateau Hardangervidda, which is the main water source for many hydroelectric power plants in this part of southern Norway. The elevation ranges between 800 and 1800 m a.s.l. In spite of the low sun elevation (49 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 on the eastern side of the main catchment areas. Power stations are mainly located in these depressions in the landscape.



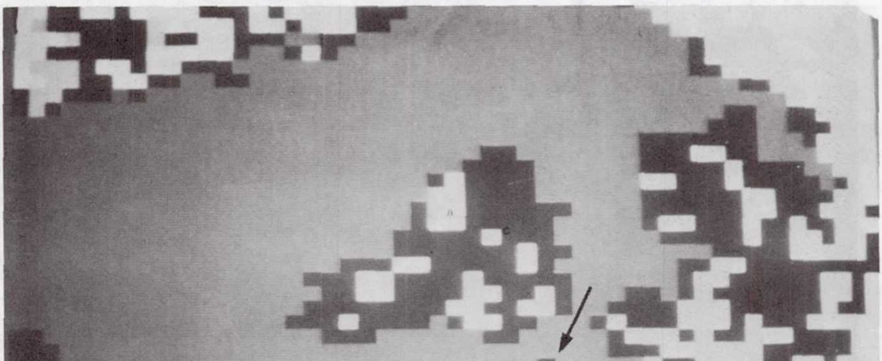


Figure 5 a. Oblique photograph from aircraft of the test area Kjela, taken on July 8, 1975. Typical landmarks are the highway and islands in the lake.

b. On the following day, July 9, the same area was imaged by Landsat for the purpose of determining the exact location of the snow limit. When the Landsat data is reproduced at full resolution (60 x 80 m), individual patches of snow on the two islands can almost be recognized (2168 - 10032).

The result of this work is shown in Figure 6, and the curve best fitted to the data can be expressed:

$$Q = 128\,(e^{0.0018\,R} - 1)$$

Q = subsequent runoff ($10^6\,m^3$)

R = snow-covered area (km^2)

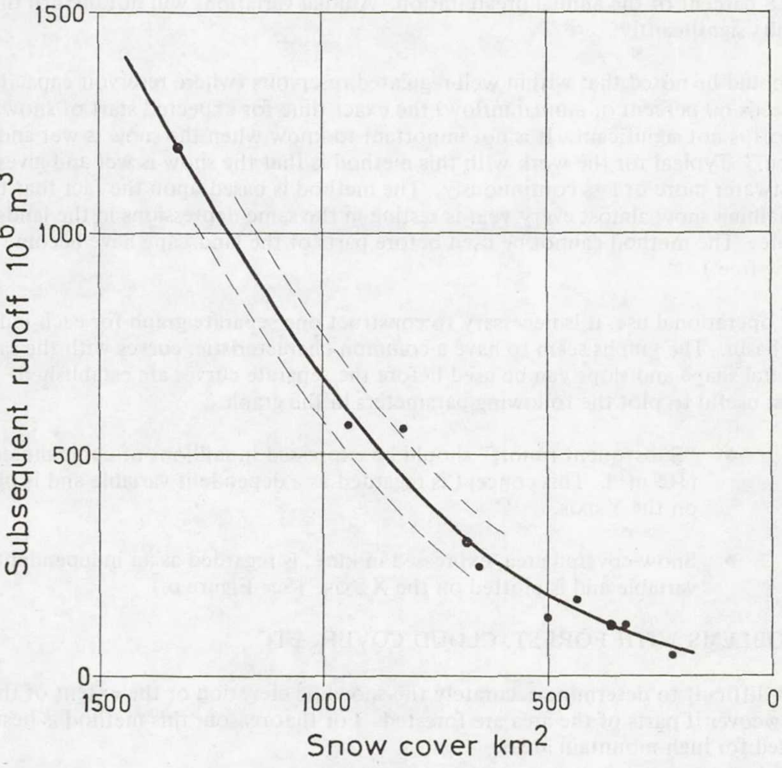


Figure 6 Experience has shown that it is possible to combine results obtained at various power plants in Norway in the same diagram. Subsequent runoff is plotted as a function of snowcover. Instead of calculating the percentage of snowcover in the catchment, it seems sufficient to determine the snow-covered area in square kilometers. 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 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 snowcover. The lowermost would show the situation in years of very thin snowcover.

The subsequent runoff (Q) can then be determined when the snow-covered area (R) is known, for any area with the same characteristics as the test areas.

Experience has shown that if the extent of snowcover is determined from all four Landsat bands, there are significant differences in the results. MSS 4 gave the largest snowcover, but only slightly more than MSS 5. MSS 6 and MSS 7 gave the smallest snow areas. MSS 5 was selected as the best band for snow mapping.

All measured runoff values should be corrected so that they express the runoff with a "normal" precipitation included, as this will make future use of the graphs simpler and quicker. In June and July, the precipitation is normally low, on the order of 14 to 18 percent of the annual precipitation. Annual variations will not disturb the results significantly.

It should be noted that within well-regulated reservoirs (where reservoir capacity exceeds 60 percent of annual inflow) the exact time for expected start of snowmelt runoff is not significant. It is not important to know when the snow is wet and "ripe." Typical for the work with this method is that the snow is wet and gives off meltwater more or less continuously. The method is based upon the fact that the remaining snow almost every year is resting in the same depressions in the landscape. (Note: The method cannot be used before parts of the landscape have become snow-free.)

For operational use, it is necessary to construct one separate graph for each individual basin. The graphs seem to have a common characteristic; curves with the same general shape and slope can be used before the separate curves are established. It is most useful to plot the following parameters in the graph:

- "Subsequent runoff" should be expressed in millions of cubic meters ($10^6 m^3$). 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 Figure 6.)

PROBLEMS WITH FOREST, CLOUD COVER, ETC.

It is difficult to determine accurately the snowline elevation or the extent of the snowcover if parts of the area are forested. For that reason, this 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 special effects of shadows.

Clouds are another disturbing factor because they appear in the imagery with the same grey tones as the snowcover. Separation of clouds from snow and ice can be done visually due to cloud shadows and the special shape of clouds. An automatic differentiation does not exist today and will probably be difficult to develop with the sensors available.

A test was made to determine how much of the snowcover on the mountain plateau Hardangervidda in southwestern Norway was in shadow when the whole area was covered with snow. The image 2024-10034 obtained on February 15, 1975, had a sun elevation of 14 degrees. The area is relatively flat, and less than five percent of the area was then covered by shadows.

The snowmelt from this area starts approximately in the middle of May each year, and the use of satellite data will be most interesting in June and July, when the sun elevation has increased to 45 to 50 degrees. Thus, shadows are not considered a problem unless we approach areas of more broken topography which also exist in Norway.

NOAA-VHRR/TIROS-AVHRR IMAGES

After preliminary work with Landsat imagery, attention was focused on NOAA-VHRR imagery. In the spring of 1978, a National Partnership Project (NPP) was initiated between the Norwegian National Committee for Hydrology (IHP) and IBM to develop methods for snow mapping using Landsat, NOAA, and TIROS digital data.

The work has been performed using the IBM/ERMAN-2 interactive system connected to an IBM 370/158 computer. The imagery can be fully manipulated and displayed on a color monitor. Final results are presented as tabular values and plotted maps.

The NOAA/TIROS images can be obtained almost every day, a fact which is most important for Scandinavia, where complete or partial cloud cover is common. When working digitally the pixel (picture element) size is satisfactory, except for small watersheds (Figure 7). It was found that the use of photographically enhanced NOAA imagery did not satisfy the requirements for snow mapping. If data are used digitally, it is not satisfactory to classify each 900 m x 900 m pixel as either snow-free or snow-covered because more information on snowcover for each pixel is available.

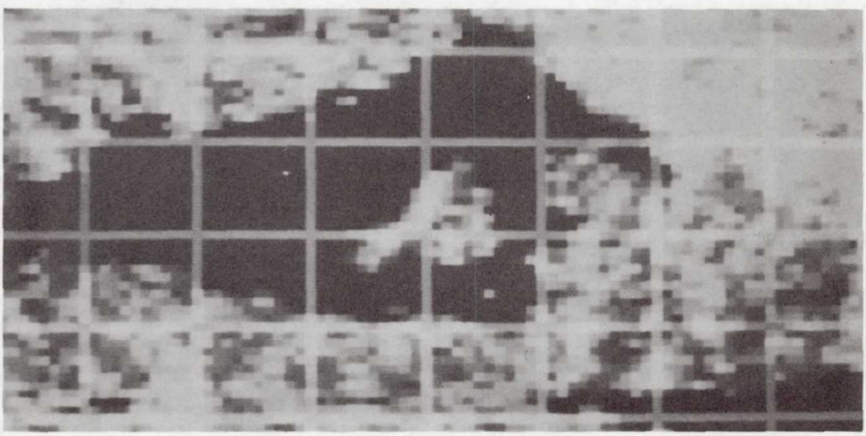


Figure 7 The same Landsat image as shown in Figure 5b with the 900 x 900 m resolution grid of NOAA or TIROS superimposed. This resolution seems to be well suited for larger areas.

To solve this problem, we might consider a square on the ground 900 x 900 m in size, covered by dark soil and some small bushes, which is normal for the high-mountain basins. If this area is gradually covered by 1/10, 2/10, 3/10, etc., of snow, the reflectance from the area will also increase up to a value which, finally, corresponds to a complete snowcover. The reflectance of the area will therefore change from that of soil to that of snow, depending on the snow/soil ratio (Figure 8).

Such intermediate values are very useful because they can be utilized to estimate the snowcover more precisely. Data are used to indicate the percent snowcover within each pixel, and the results can be presented as plotted maps and in a tabular form. This method was used in a semioperational mode for the first time in 1977.

The average size of the larger catchment areas in Norway are on the order of 1,000 km^2. Digital enhancement of VHRR imagery was therefore required to make the data useful for snow mapping. The following procedure is now being tested for determining the areal extent of snowcover:

1. A digital description of each catchment area (coordinates) is stored in the computer and registered to UTM projection.
2. VHRR-VISIBLE data are read from magnetic tape. A subset is made of the area of interest. Geometric correction and registration to UTM projection are performed using well-distributed ground control points.
3. Training fields are selected in snow-free areas and in areas with full snowcover (2 to 4 of each kind). Each field contains 20 to 40 pixel. The mean response for the two types of fields are computed. The response interval between the two values is divided in classes: 0-20, 20-40, 40-60, etc., percent snowcover, assuming a linear relationship.
4. Each catchment area is termed a test field, and a classification is made for each test field using the registered data.
5. The result is a printout showing the distribution of snow within each catchment area and the total snowcover for each area in a tabular form.
6. This result is compared with a curve giving the relationship between areal snowcover in square kilometers and subsequent runoff. The information is transferred to the user.

The spectral reflectance value of soil/vegetation for VHRR data has been approximately 10, and for full snowcover approximately 100. This will give an interval of 90 steps which is 35 percent of the full 1 to 255 value range.

The NOAA/TIROS receiving stations in Lannion, France, and Tromsoe, Norway, have provided digital VHRR data for the project. A day-pass image is now available at the computer within 20 hours. The results should reach the user the following day.

The second phase of the NPP project is to investigate further the relationship between areal extent of snowcover and subsequent runoff. Information obtained from Landsat at an earlier stage as well as filed NOAA-VHRR data are now used for this purpose.

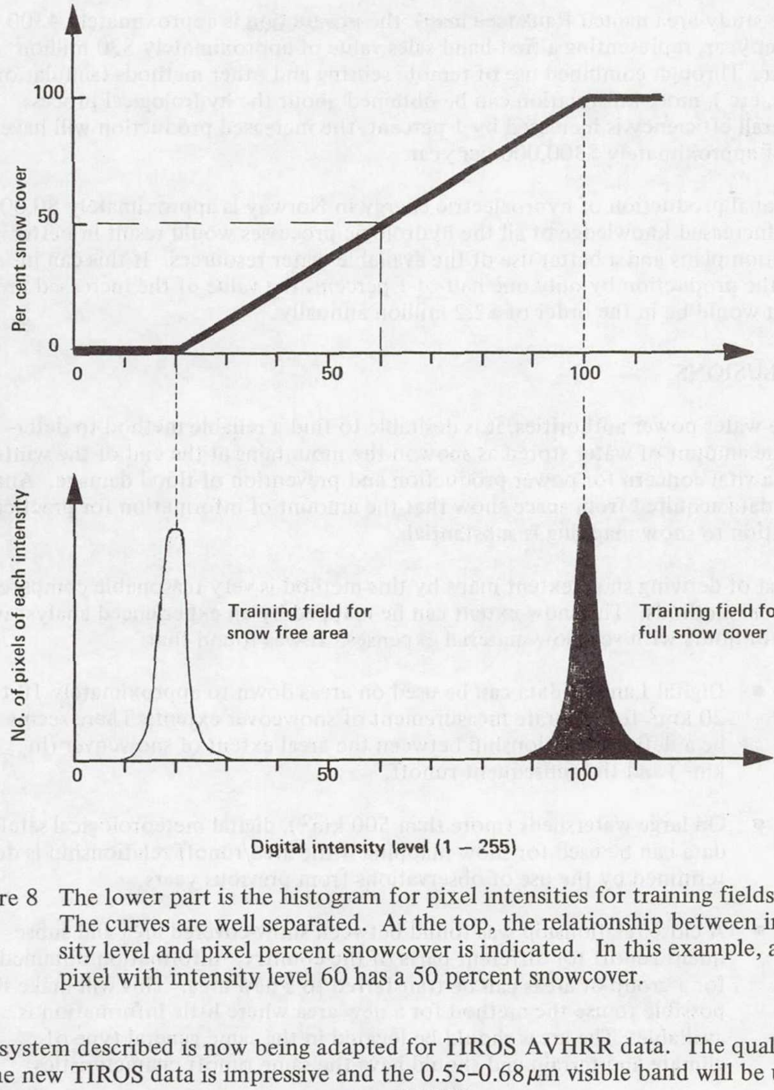


Figure 8 The lower part is the histogram for pixel intensities for training fields. The curves are well separated. At the top, the relationship between intensity level and pixel percent snowcover is indicated. In this example, a pixel with intensity level 60 has a 50 percent snowcover.

The system described is now being adapted for TIROS AVHRR data. The quality of the new TIROS data is impressive and the 0.55–0.68 μm visible band will be used for the snow mapping during the summer of 1979.

COST-EFFECTIVE BENEFIT

Determining the economic value of data acquired from space is difficult, but some examples will illustrate the benefits. The mean annual production of electricity at the Røssåga power plant in north Norway is 2470 GWh (2470 million kWh). If the use of space-acquired data could prevent the loss of 1 GWh and instead route it through the turbines, the increased energy production would then represent a first-hand value of approximately \$10,000, but the final value will be even higher.

For the study area named Rana (see map), the production is approximately 4300 GWh per year, representing a first-hand sales value of approximately \$30 million per year. Through combined use of remote sensing and other methods (simulation models, etc.), more information can be obtained about the hydrological process. If the overall efficiency is increased by 1 percent, the increased production will have a value of approximately \$300,000 per year.

The annual production of hydroelectric energy in Norway is approximately 80,000 GWh. Increased knowledge of all the hydrologic processes would result in better production plans and a better use of the available water resources. If this can increase the production by only one-half of 1 percent, the value of the increased production would be in the order of \$2.2 million annually.

CONCLUSIONS

For the water power authorities, it is desirable to find a reliable method to determine the amount of water stored as snow in the mountains at the end of the winter. This is a vital concern for power production and prevention of flood damage. Analysis of data acquired from space show that the amount of information for practical application to snow mapping is substantial.

The cost of deriving snow extent maps by this method is very reasonable compared to manual methods. The snow extent can be mapped by an experienced analyst in a couple of hours with very low material expenses. It was found that:

- Digital Landsat data can be used on areas down to approximately 10 to 20 km^2 for accurate measurement of snowcover extent. There seems to be a definite relationship between the areal extent of snowcover (in km^2) and the subsequent runoff.

- On large watersheds (more than 500 km^2), digital meteorological satellite data can be used for snow mapping if the area/runoff relationship is determined by the use of observations from previous years.

- A close relationship was found between snow-covered area and subsequent runoff for different parts of the country. Information obtained for a group of areas can be transferred to a new area. This will make it possible to use the method for a new area where little information is available. The areas should be located in the same general type of climate and terrain and should have the same runoff characteristics.

- The relationship developed (see above) is quantitative, and the result is an important parameter in hydrologic runoff models. It is a great advantage that the data can be easily obtained and are easy to handle. The importance of such methods increases with the increased cost of energy.

It is difficult to determine the economic value of data acquired from space 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 of 1 percent will have a great economic value.

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