**Arbeitsberichte der Schweizerischen Meteorologischen Zentralanstalt**
**Rapports de travail de l'Institut Suisse de Météorologie**
**Rapporti di lavoro dell'Istituto Svizzero di Meteorologia**
**Working Reports of the Swiss Meteorological Institute**

**Zürich**

No. 49

# Measurement of the Water Equivalent of the Snowpack

Papers presented at the International Symposia on the Rôle of Snow and Ice in Hydrology
6. 9. - 13. 9. 1972 in Banff, B.C. Canada

by

Peter Rauh, Zurich

Decembre 1974

Meteorology 551. 578. 46


## Zusammenfassung

In dieser Semesterarbeit ( ETHZ, Geographisches Institut, Hydrologie ) werden die gebräulichen Methoden der Messung von Schneedichte und Wassergehalt der Schneedecke kurz beschrieben. Neun Beiträge, die am " Symposium über die Rolle von Schnee und Eis in der Hydrologie " in Banff 1972 vorgetragen wurden, befassen sich mit der Messung des Wasserequivalents von Schnee. Diese Beiträge werden zusammengefasst und kommentiert, wobei die Frage gestellt wird, ob wirklich neue Methoden erarbeitet wurden.

## Summary

In this work as part of a course in hydrology taken at the Federal Polytechnical Institute in Zurich the methods for measuring the water equivalent of the snowpack are described. Nine papers on this topic were presented at the " Symposium on the Rôle of Snow and Ice in Hydrology ". They are summarised, commented and studied to find original methods.

Riassunto

In questo lavoro semestrale ( SPF - Z, Istituto Geografico, Idrologia ) vengono descritti brevemente i metodi di misura della densità della neve e il contenuto acqueo del manto nevoso. Nuovi contributi, presentati al " Simposio sull'importanza della neve e del ghiaccio nell'idrologia " a Banff nel 1972, trattano la misura dell'equivalente acqueo della neve. Questi contributi vengono riassunti e commentati e viene posta la domanda, se veramente siano stati elaborati nuovi metodi.

Résumé

Le travail semestriel ( EPFZ Institut de Géographie, Hydrologie ) décrit brièvement les méthodes usuelles de mesure de la densité de la neige et de son contenu en eau.
Au " Symposium sur le rôle de la neige et de la glace en hydrologie " tenu à Banff en 1972, neuf des travaux qui furent présentés concernèrent le problème de l'équivalence en eau de la neige. Les travaux sont ici résumés et commentés et la question de savoir s'il s'agit vraiment de nouvelles méthodes est posée.

# Measurement of the Water Equivalent of the Snowpack

## I. Introduction

Measurement and areal estimation of the water equivalent of the snowpack is of high importance to hydrometeorologists. Accurate data provides the base for forecasting runoff during snowmelt, planning hydroelectric power stations and earth resource programmes.
It is only in the last one or two decades that new methods of measuring water equivalents of the snowpack have been developed. Nuclear chemistry and electromagnetic theories are now applied as well as conventional physics. The problem of remote sensing and areal representativeness is being investigated.
The aim of this work is to summarise the conventional and new methods applied for measuring water equivalents. At the Banff symposia on the rôle of snow and ice in hydrology nine papers were presented on this topic, seven of them personally. The papers are summarised, note taken of the discussion which followed the reading of them, and studied to find original methods.

## 2. Methods in use

A snow course is a " permanently marked area where snow surveys are taken each year ", [ 10 ]. It should be selected so that the measurements provide a good sample representing a certain area of the basin. Sites have to be chosen carefully, regarding

- topography
- elevation
- exposure
- meteorological factors
- accessibility

The length of a snow course should exceed one kilometer. In the mountains sampling points 20 to 40 meters apart give good results, more points are needed in open areas due to drifts etc. On plains snowdepth should be measured every 10 to 20 meters, samples taken every 100 to 200 meters.

## 2.1 Sampling Equipment

### 2.1.1 Sampling tube with cutter and weighing apparatus

Most commonly a plastic or metal tube with a diameter of about 4 cm for snow depths above one meter or 8 cm for depths below on meter is used. To ensure smooth sampling a cutter is attached to the bottom end of the tube. After the sample is taken, tube and snow core are weighed. As the weight of the tube is known, the water equivalent can easily be derived. The accuracy of this system is about ± 10 grammes.

### 2.1.2 Snow Scales

A flat surface, mostly parallel to the ground, is exposed to the atmosphere for collecting snow. The plate plus snow is weighed continuously giving records of the water equivalent. Errors may be caused by radiation and snow drifts.

### 2.1.3 Gamma ray method

Attenuation of gamma rays depends on thickness and density of snow, hence its water equivalent. A gamma ray source, usually Cobalt or Caesium, is placed level on the ground and vertically above it a Geiger - Müller counter. Impulses from the detector are transmitted to a scaler or recorder. Occasionally a source is inserted some distance into the top soil. In this case soil moisture and water equivalent of the snowpack are measured simultaneously. In order to avoid temperature influence on the detector, the GM counter is placed on the ground and the source above the maximum expected snow level.
Most textbooks ( eg. Bruce and Clark [ 11 ], Wiesner [ 12 ], DeWiest [ 13 ], Linsley et al [ 14 ], etc. ) only list these three differnt methods. Recently at least two more methods have been developed and are in operational use.

### 2.1.4 Snow Pillow

A butyl rubber pillow or a pressure plate is used to measure the weight of the snow cover. From the weight and the area of the snow pillow, the water equivalent can be derived. The surface of the snow pillow is level with the surrounding ground. The pillow itself is filled with antifreeze. The pressure exerted by the snow ( presumed to be a perfect fluid ) is automatically measured and recorded or transmitted.

2. 1. 5 Natural Gamma Ray Method

Natural gamma rays emitted by the Earth itself are used in this method. With the gross count method or spectral analysis the attenuation of the gamma rays exerted by the water content of the snow and the top layers of the soil is measured by low flying aeroplanes. This is so far the only method which gives an areal measurement of the water equivalent along the flightpath, in contrast to all other measurements being samples at a certain point.

3. Papers presented at the symposia

3. 1. E. L. Peck : Review of methods of measuring snow cover, snowmelt [1] and streamflow unter winter conditions ( theme paper )

Peck describes in his passage on measurement of the water equivalent of the snowpack most methods listed under point 2. He emphasises the accuracy of various methods and their drawbacks :

a ) Gravimetric measurements using tubes may have an error up to plus 12 percent ( overestimating ) in areas with small snow depths.

b ) Snow pillows are relatively simple and cheap. They are excellent for remote sensing. But the assumption that the snow above the pillow acts as a perfect fluid lessens the accuracy. Development of ice lenses or pools of liquid water at the surface of the pillow affects the results too. During the primary accumulation period measurements are satisfactory.

c ) Radioisotopic gauges are accurate. The standard error for water equivalents of up to one meter may be as low as 1.8 cm. There are also horizontal snow gauges, taking a profile between two vertical poles. Source and detector are moved up simultaneously and measurements are taken at various levels above ground. A new system is developed which combines both the vertical and horizontal methods. Sources and detectors are fixed on two poles at different levels. In this case each source is serving two vertical sections. The advantage is that a shift in calibration due to radioactive decay is diminished. High cost of instruments and environmental safety aspects are the most significant drawbacks of these methods.

d ) Natural Radiation Technique : Aerial surveys may be made with reasonable accuracy up to a water equivalent of 30 cm. Low level flights are difficult in mountainous areas and measurements over forested areas are also unreliable.

3. 2. M. A. Bilello et al : [2] Mesoscale measurements of snow cover properties

During the winter 1966/67 at Fort Greely in Alaska measurements of snow-cover, snow density and snowcover temperature were taken at 19 points in a 20 by 40 kilometer area.

Snow density was measured by a 500 $cm^3$ snow sampling tube. Different layers of snow were measured seperately so that an average density at a site was obtained by relating several weighted densities of different layers and the dephts of those layers. As the snow density and depth was known water equivalents were computed. Water equivalent measurements just before the melt period were between 8 cm and 39 cm.

For best areal estimation of total water equivalent maps are drawn showing snow depth isopleths and lines of equal density.

Comment : The conventional system of snow tubes was used to measure density and water equivalent of the snowpack. However not ordinary average density but weighted density, taking account of significant differences in the vertical profile, was computed and a map with lines of equal average density was drawn up. Snow depths were measured at the same sites and a map drawn showing lines of equal maximum snow depth.

The method of weighted snow densities gives a more representative indication of water content at a specific site. However it does not solve the problem of extra-polating point measurements to areal estimates. The idea of drawing maps with lines of equal water equivalents is not really new as the same method has been suggested for rainfall measurements. To be able to produce reasonably accurate maps, a dense network of snow sampling sites is necessary.

3.3 J. N. Washichek : [3] Collection of atmospheric data for project skywater

Since 1965 the Snow Survey Unit of the Soil Conservation Service ( USA ) has been carrying out measurements of water equivalent of snow cover in three areas in Colorado and New Mexico. Conventional tube measurement and snow pillows were used.

The snow pillows had a size of 3.66 meters diameter and were filled with 1324.75 liters of methanol, 10.16cm thick. On-site recorders and transmitters were connected to the pillows. Comparisons between manual tube sampling and pressure pillow readings showed that in the Park Range Project ( 2000 to 3250 meters above MSL ) there was very little difference. Pillows showed only slightly higher water equivalents than hand readings.

For the project in Southwest Colorado a new kind of pressure pillow was used. Four 122 by 152 cm metallic pressure plates were combined to a 244 by 305 cm area. These plates are less likely to leak and are easier to repair in the field. They also take only 15 liters of antifreeze. Again results were very encouraging. Daily buildup or recession of the snowcover or individual storms can be identified.

The third project, in the Jemez Mountains, New Mexico, was so far south and at such a height that melting could occur at any time during the winter. Therefore pillow and tube readings were not sufficent.

A fulcrum weighing precipitation gauge was developed. On a 1.8 meter high pole a special selfcontaining flucrum weighing device and a precipitation bucket of 20 cm diameter were attached. Comparisons of the fulcrum method and manual weighing of the precipitation bucket showed a correlation coefficent above 0.992!

Comment : This report of the Snow Survey Unit's measuring procedures and results show how important it is to analyse the area under consideration and use the appropriate instruments. Snow pillows give satisfactory results in areas with reasonably large snowpack and temperatures not allowing melting processes before spring. New pressure plates are developed and increase the reliability of this method of measuring water equivalents. For regions with melting processes going on during the winter season precipitation gauges have to be used in order to obtain best results, combined with snow pillows.

3.4 R. Lemmelä : Measurements of evaporation, condensation and
[4] melting from a snow cover

As part of a large investigation concerning the snowmelt and its influencing factors water equivalents of the snow cover have been measured in an area in southern Finland, 60 meters above MSL.
Snow density was measured with a cylinder of 100 $cm^2$ cross section and a set of snow scales. For measurements of density gradients smaller tubes were used.

After December 1968 snow pillows were used as well. The pillow had a surface of 10.5 meter square. It was filled with water and ethanol and made of rubber. The level of the fluid was recorded by a limnigraph. Correlation factors of pillow and weighing measurements were 0.999 in 1969, the standard deviation 4.1mm. The snow pillow showed a total precipitation of 30% more than a nearby conventional precipitation station at the time of maximum water equivalent or 50% more than an ordinary precipitation gauge.
No recording rain gauge had been set up at the pillow site. So it was not possible to determine the time lag of increasing load. Reaction of decreasing load due to melting and runoff was checked by comparisons with meltwater drip pans. Compared with the pans the pillow showed a lag of almost an hour.

Comment : It is impressive to see how much the different factors measured simultaneously are related to one another. More experience is gained by checking pillow readings with drip pans. Accuracy and time lag are better verified.

3.5 B. Hasholt : Random sampling techniques applied in measuring
[5] snow water equivalent in a drainage basin

As in Denmark snow depths are relatively small, tubes and scales have much smaller dimensions than in regions with a larger snowpack. Inside diameter of the tube is 60 mm, length 20 to 25 cm. The spring scale has a capacity of 500 grammes. For standard deviations of ± 2 mm for length, ± 2 g for weight and ± 0.2 mm for diameter of the tube, a sample of 100 mm, snow depth of 105 mm and a sample weight of 100 grammes the final standard deviation of the water equivalent is ± 4 percent.
The random sampling technique uses statistical methods. A gridnet is superimposed

on the map of a drainage basin. In some squares a number of independent points are chosen where measurements are carried out. The number of squares and points in those squares chosen depends on the confident limits required. Comparisons between measurements at random chosen sites and computed values from observed snow precipitation and snow melt show a difference of about 8 to 10 percent. In both cases listed the statistical method overestimated the mean water equivalent.

Comment : Not only great snow depths but also small ones present problems to measuring water equivalents of the snow cover. Special tubes and scales have to be developed and used. The method of choosing measuring points at random thus obtaining an areal mean with a preselected confidence limit may be well applied in relatively flat and homogeneous basins. Mountainous and variable basins however present many more difficulties. But statistical knowledge certainly helps to find sites for snow courses in order to obtain maximum possible representativeness.

3.6 P. D. Randolph et al : [ 6 ] A network of telemetered profiling isotopic snow gauges

Four profiling isotopic snow gauges were fabricated at Aerojet Nuclear Company and set up at Mt. Baldy near Ketchum, Idao ; at Red Mountain Pass, Colorado ; at Mt. Hood, Oregon and at Donner Pass. Customers of the data of these four sites used the profiles mainly to estimate and forecast runoff conditions during the snow melt season.

The profiling isotopic snow gauge was originally constructed by J. L. Smith of the US Forest Service. The version used here consists of two vertical access tubes 66 cm apart. The source is a 137 - cs - 661 - keV photopeak, the detector of the scintillation type. At the bottom of the vertical tubes there is a lead standard absorber for calibration before profiling. Source and detector are lifted simultaneously. A run is made up of 1.27 cm steps ( . 5 inch ) and at 9. 5 cm heigth per minute. Heights up to 7. 3 meters may be reached.

The electronic system is designed for temperatures ranging from minus 35 to plus 22 degrees Celcius, and for telemetric purposes. The data obtained by the snow gauge when interrogated are digitally transferred to a field control unit which then transmits them to the base station computer either by telephone or wireless. At the base station measurements of density and water content up to the level reached are printed out for each step. On a X - Y - recorder density profiles are plotted. At the end of each run average density and total water equivalent are worked out as well as snow depths. Both commercial power supply or a remote power soucre may be used. The gauge uses 1.8 Watts in standby position and 7.8 Watts in full operation.

During the 1971/72 snow season 40 to 50 profiles were set up at all but the Donner Pass station. The 3 gauges were out of use for 59 days, mostly due to easily repairable faults and waiting time for personnel and spares.

This experiment shows that profiling isotopic snow gauges may very well be used as remote sensors in rather hostile environment. Accuracy has been satisfactory. The problem of sun cup formation around the top of the access tubes may partly be overcome by insulating with white paint.

In the discussion which followed the questions of errors due to

- machanical dislocation of the access tubes by snow pressure
- formation of sun cups and errosion holes around tubes
- rain water dripping down the tube end freezing

were raised as well as that of cost.

Comment : In this field experiment the operational use of telemetric profiling isotopic snow gauges has been proved satisfactory although there are serious drawbacks which were mentionned in the discussion. The problem of mechanical damage may be overcome by additional support of the access tubes but this will increase the formation of suncups. Errors due to sun cups are significant at times of small snow depths and in the spring melting period. Relatively high cost will also limit the use of this system.

3.7 W. Attmannspacher et al : [ 9 ] not read — Remote sensing of water content of snow cover at one or more points in a mountainous area

Experiments with an artificial gamma ray source and a GM detector have been carried out at the Hohenpeissenberg in western Germany. The source was a Cs 137 with a half-life of 30 years. The transmission set was so designed that for each run only the step from count 9999 to 10'000 was transmitted to the base station thus recording the time needed to reach 10'000 counts.
The experimental field also contained a 6. 25 $m^2$ snow balance, and manual measurements with the snow tube were carried out. The gamma ray gauge was calibrated with a plastic container holding different amounts of water.
Results of the 1970/71 season showed that the radiation gauge registred the same water equivalents as the balance during the accumulation period, in February and March however there were considerable differences which were mostly due to snow drifts.
Comment : The use of the gamma radiation gauge and its electronic system is tested with reasonable success at a mountain site. Results show however the problems of point measurements being affected very much by local influences such as snow drifts etc. Representativeness is a big problem.

3.8 A.V. Dmitriev et al : [ 7 ] not read — Practical use of aircraft gamma ray survey of snow cover in USSR

The aircraft gamma ray technique was first proposed in 1962 in USSR, in the winter 1965/66 first operational use was made of this new method.
The natural gamma ray survey is like the isotopic snow gauge based on the snow's absorption of radiation. The gamma radiation is emitted by the natural radio-active elements in the top 30 to 40 cm of the ground. Basically pre-snow cover values of radiation intensities are compared with values measured during various stages of snow cover ( build up, maximum cover, melting period ).
To determine the gamma ray intensity related to the snow cover two sets of instruments are needed : one to collect data mainly from the soil-ground sources, the other for interfering atmospheric radiation.

The two great advantages of this method are :

- The absorption does not depend on the aggregate conditions of the water, and the water content of the top soil is measured as well as that of the snow cover.
- The counter averages data of a band roughly 300 meters wide with a length equal to the flight path.

This should provide us with a much more representative measurement of the areal distribution of the total water equivalent available for runoff. Accuracy depends on instrument performance, flight altitude ( 50 to 75 meters ), soil - ground moisture variations, air radioactivity variation, navigation errors and statistics used. This new technique produces snow cover maps ( seperately for fields, forested and total area ) during the period of accumulation and maximum snow cover, water equivalent data over the same areas and periods and residual snowpacks and meltwater determination at the time of snow melt. To survey a zone of 300'000 to 350'000 km$^2$ one aeroplane and 5 to 10 days are needed.

As an example data of the season 1968/69 was displayed where an area of about 2 million km$^2$ was surveyed. There were six zones set up and two aircraft of the type JL 14 in use. In general the data acquired by airborne survey showed a significant higher water equivalent available for runoff than ground survey at the same time and at the same places. However there were great variations depending on

a ) homogeneity of the snow cover

b ) climatological circumstances

c ) topography

d ) vegetation

The most striking fact was the significant increase in the difference between air - and ground - survey data with decreasing latitude. In the northern territories there was little formation of ice lenses or meltwater at times of maximum snowpack, whereas further south the amount of water stored in ice lenses and in the liquid state at the surface and in the top soil is considerable. Ground survey methods ( tubes and pillows ) do not take into account these resources but gamma ray techniques do.

Comment : This method using natural gamma radiation to determine the water equivalent of the snowpack and water in the top soil is so far the only new way to arrive at an areal estimate rather than an accurate measurement at one point. Theoretically it would be possible to measure a whole basin in strips of 300 m width and various lengths thus obtaining an accurate value for the total water stored above and in the ground.

However there are a number of difficulties to overcome, such as :

- the accurate determination of the influence of the vegetation ( forest eg. )
- the problem of position in respect to space and time ( variations )
- the problem of aircraft use and safety regulations in mountainous territories and
- the cost.

3.9 W.I. Linlor : Snowpack water content by remote sensing [ 8 ]

The dielectric constant ( or permittivity ) and the loss tangent are the most important electrical properties of snow in respect to electromagnetic response. The dielectric constant is very much related to the snow density. The loss tangent is dependent on the percentage of liquid water available in the snow.

On a graph showing reflection coefficient versus frequency of electromagnetic waves reflected normally from a plane surface covered with water in different aggregate conditions ( water, ice, snow ), there are various significant dips. The frequency at which these dips occur is a function of the snowdepth and its refractive index which is proportional to the square root of the dielectric constant of snow. The depth or amplitude of the dip is again a function of the dielectric constant of water, ice and snow with only a slight dependency on the thickness of ice layers or loss tangent of snow. Dielectric constants of water and ice are known and fairly constant. Therefore the dielectric constant of the snow can be determined. Laboratory tests may relate dielectric constants with various snow densities. In this way snow density and snow depth can be determined uniquely from the value of the " dip frequency " and " dip amplitude ".

Density and depth of the snowpack together result in the water equivalent. Theoretical models have been put up giving encouraging results on computer runs.

Field experiments are now necessary to verify the results and for calibration reasons. On a wooden tower a source of electromagnetic waves and a receiver were installed. Emitting power and frequency were kept constant. Snow was shovelled on to the surface which reflected the electromagnetic waves. Incoming power was plotted against the increasing snow depth. This was done for moist and very wet snow. The dips occured at 92 cm snow depth for a frequency of 290 MHz. The dip of the very wet snow was much deeper than that of the moist snow.

In the discussion the question of installing source and receiver on an aircraft arose. Resolution at a flight level of 3000 ft would be about the size of a football field.

Comment : This new method of determining the water equivalent of the snowpack by use of electromagnetic waves is still in the early experimental stage. It seems however that in future development and application in operational circumstances are well possible. Like the method of natural gamma ray detecting it will have the invaluable advantage ( if mounted on an aircraft ) of giving areal results of the water equivalent rather than point measurements. However there are the same problems concerning vegetation, localising, flight safety and cost.

## 4. Conclusions

The review of the nine chosen papers presented at the Banff symposia demonstrates the importance that hydrologists give to the measurement of the water equivalent of the snowpack. The papers make obvious the need for more accurate determination of the water content.

1 ) The conventional sampling tube and weighing apparatus were still used. Methods of obtaining better areal representativeness were tested, applying statistical knowledge, or finer instruments meeting the needs of the individual areas.

2 ) The three new methods recently developed ( pillow, gamma ray gauge and natural gamma ray technique ) were further tested and put into operational use. Results were presented which allow comparisons with the conventional methods.

3 ) The problem of remote sensing was attacked very intensively. Electronic equipment was developed to ensure smooth data collection under hostile environmental conditions and for day to day use.

4 ) A completely new method was presented, based on the electromagnetic properties of the water in various aggregate conditions. Calculations with theoretical models have given encouraging results. Practical test are now being carried out.

5 ) Two methods ( natural gamma ray technique and electromagnetic reflection ) allow the use of airborne equipment, thus obtaining true areal measurements of the water equivalent.

Bibliography


[ 1 ] E. L., Peck : Methods of measuring snow cover, snowmelt and streamflow under winter conditions. Unesco - WMO - IAHS, Banff, 1972

[ 2 ] M. A., Bilello, R. E., Bates and J., Riley : Mesoscale measurement of snow - cover properties. Unesco - WMO - IAHS, Banff, 1972

[ 3 ] J. N., Washichek : Collection of atmospheric data for Project Skywater. Unesco - WMO - IAHS, Banff, 1972

[ 4 ] R., Lemmelä : Measurement of evaporation - condensation from a snowcover. Unesco - WMO - IAHS, Banff, 1972

[ 5 ] B., Hasholt : Random sampling technique in measuring snow - water equivalent in a drainage basin. Unesco - WMO - IAHS, Banff, 1972

[ 6 ] P. D., Randolph, R. A., Coates, E. W., Killian, L. O., Johnson and R. L., Heath : A network of telemetered profiling isotopic snow gauges. Unesco - WMO - IAHS, Banff, 1972

[ 7 ] A. V., Dmitriev, R. M., Kogan, M. V., Nikiforov and Sh. D., Fridman : Practical use of aircraft gamma - ray survey of snow cover in the USSR. Unesco - WMO - IAHS, Banff,1972

[ 8 ] W. I., Linlor : Snowpack water content by remote sensing. Unesco - WMO - IAHS, Banff, 1972

[ 9 ] W., Attmannspacher and J., Riedl : Remote sensing of water content of snow cover at one point or more in a mountain area. Unesco - WMO - IAHS, Banff, 1972

[10] WMO : Guide to hydrometeorological practises. Technical Note 168, Geneva, 1970

[11] J. P., Bruce and R. H., Clark : Introduction to Hydrometeorology. Oxford, 1966, Pergamon Press

[12] C. J., Wiesner : Hydrometeorology. London, 1970, Chapman and Hall

[13] R.J.M., DeWiest : Geohydrology. New York, 1965, Wiley

[14] R. K., Linsley : Applied Hydrology. New York, 1949, McGraw Hill