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MEASUREMENT OF SNOW AND ESTIMATION OF SNOW COVER

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ABSTRACT

The rivers draining out of the Himalayan region derive a major portion of runoff from snow and ice melt. For runoff forecasting, irrigation planning, supply of drinking water and industrial use etc. reliable and adequate information on snowfall and snow cover as well as their water equivalent is required. Knowledge of the physical characteristics of the snow cover such as its density, depth and temperature, and their variability in time and space is necessary for hydrologists. A careful survey of snow covered area with its water equivalent in conjunction with observations of atmospheric factors can also lead to flood forecasts and general hazard warning.

Snow cover is a residual project of snowfall and has characteristics different from those of freshly fallen snow. The snow surveys made by traditional methods involve much time and labour. The advent of remote sensing has opened up new avenue for snow cover monitoring and assessment. Once a correlation between areal extent and ground truth has been established, the prediction models can be extended with suitable modifications to other areas where ground truth is not available. With adequate knowledge of gauge characteristics and limitations, gauge catch deficiencies may be minimized and reasonable data adjustments could be made. Further studies to find out the effect of weather and exposure on snowfall measurements are required to achieve improvement in catch efficiency of the snow gauges.

There is need for basic research on snow cover accretion and depletion, and their relation to meteorological and terrain factors. The development of appropriate techniques would require investigations through entirely new approaches free from the deficiency caused by poor exposure and redistribution problem. The point measurements made in representative locoation is critical for interpretation and applying point measurements as areal indices. Moreover, studies correlating snow covered area and subsequent meltwater runoff would

set the pace for further application of satellite data in this important area of hydrology.

1.0 INTRODUCTION

Snowfall and snowcover observations are indispensable to water resources development and management. In India about 80% of the total area of Himalayas is covered by snow. It is observed that snowfall is fairly high during the months of December to February. Occasions are not uncommon when snowfall occurs even in the months of October and November. The accumulation of snow reaches its maximum by March whereafter it starts melting.

Forecasts of floods and runoff in snow-fed streams require the data of snowfall and snow cover available for long periods. Such data is also used on a real-time basis for predicting avalanches and for planning transporation operation. Regional studies concerned with agriculture, ecology and climatology also need such data essentially on a seasonal basis.

For a proper appraisal of the snowfall and snowcover it is also necessary to have a knowledge of the design characteristics and limitation of the instruments used for measuring snowfall depth and water equivalent. Besides, it is also necessary to have a thorough assessment of the techniques and procedures used in measurements of the point values and estimation of areal values of snowfall and snowcover. The present review covers the measurement techniques and instruments used for the determination of snowfall and snowcover depth and their water equivalent.

2.0 REVIEW

2.1 Snow and Snowcover

The formation of snow in the atmosphere depends on many variables, the most important being that the ambient temperature must be less than $0^{o}C$ and that super-cooled water must be present. The flow diagram shown in Fig.1 outlines the process which produce different type of snow. The shape of an ice crystal is determined by the temperature at which it grows whereas its rate of growth and secondary crystal features are determined by the degree of supersaturation. The classification of the natural snow crystals has been illustrated in Fig.2. Recently Colbeck (1986) proposed a new classification system that is based on snow metamorphism. Many crystals could simply be called grain clusters, melt-freeze particles or slush in wet snow cover and faceted or rounded in a dry snow cover. Problems arise in a wet snow cover because many particles are neither distinctly melt freeze particles nor grain clusters and in a dry snow cover because ice particles often have both rounded and faceted portions.

Of the other physical properties of snow, those which are of most interest for hydrological calculations are its thermal and radiational properties and also its water-retaining capacity.

Thermal capacity and thermal conductivity of snow :

These properties of snow determine the amount of heat necessary for the melting of a given snow layer, as well as the rate of the melting. The thermal conductivity of snow depends on its structure and density but it is generally low. Because of this, snow protects the soil from freezing to a great depth and from rapid temperature fluctuations. Several formulae have been proposed to determine the coefficient of thermal conductivity of snow.

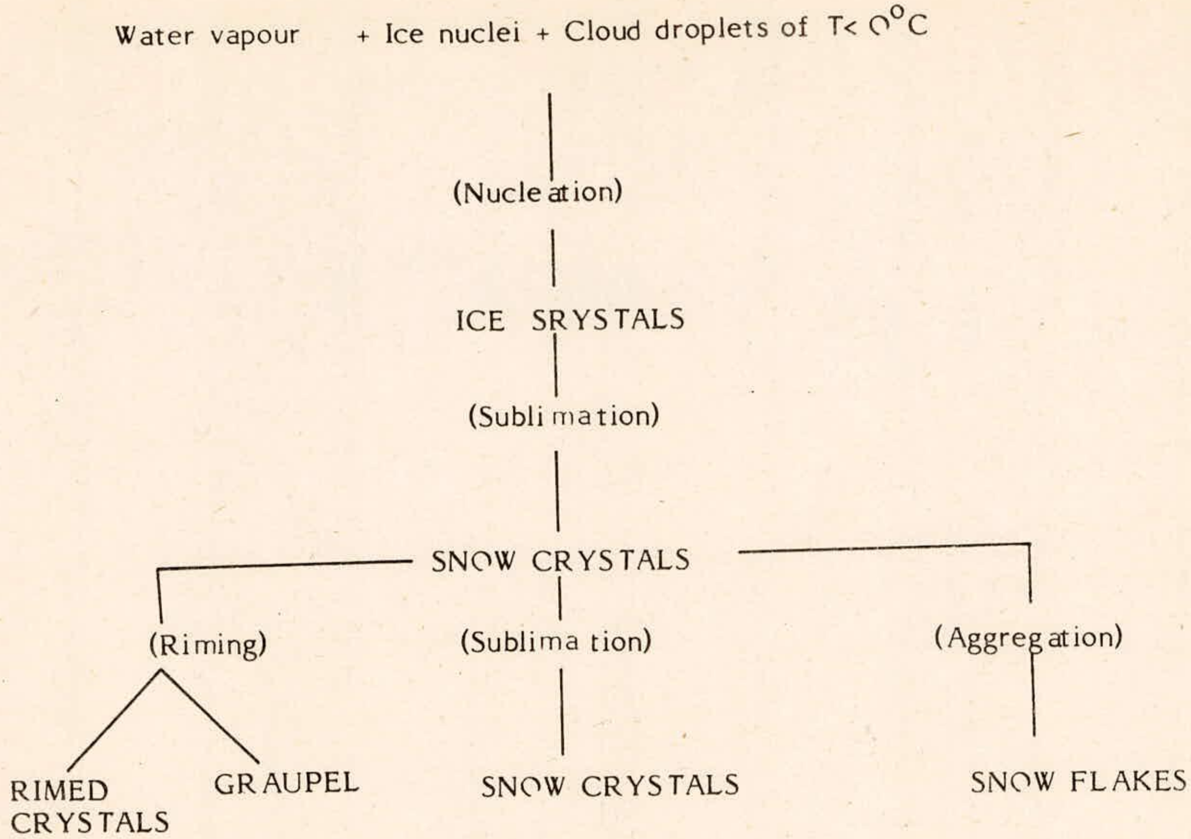


Fig.1 : Snow diagram of the formation of different types of snow

The simplest of them is Abel's formula:

$$\lambda = 280.4\ \rho^2 (J/m^2\ sec\ ^oC\ cm) \qquad ..(1)$$

where, ρ is the density of snow

Radiational properties of snow:

These properties play an important part in the melting of snow. Of these.

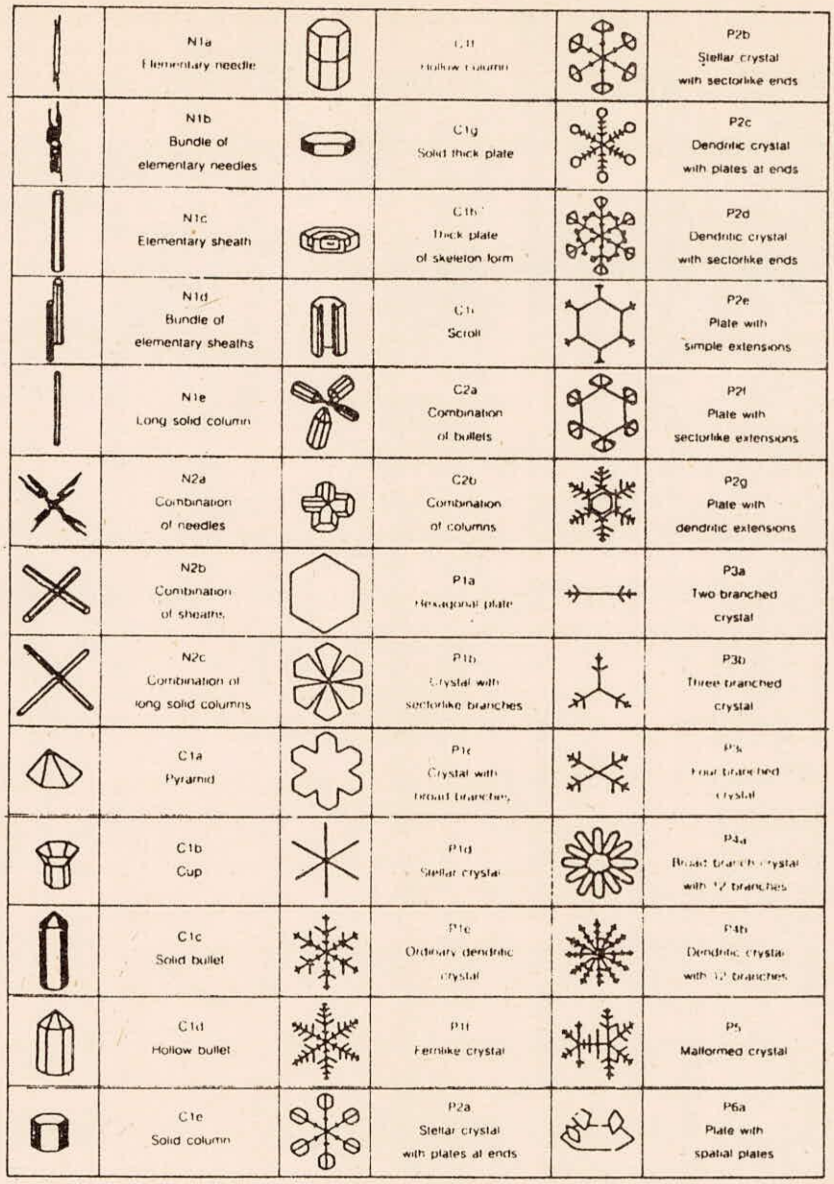


Fig. 2(a) Classification of natural snow crystals
(Reproduced from Gray and Male 1981)

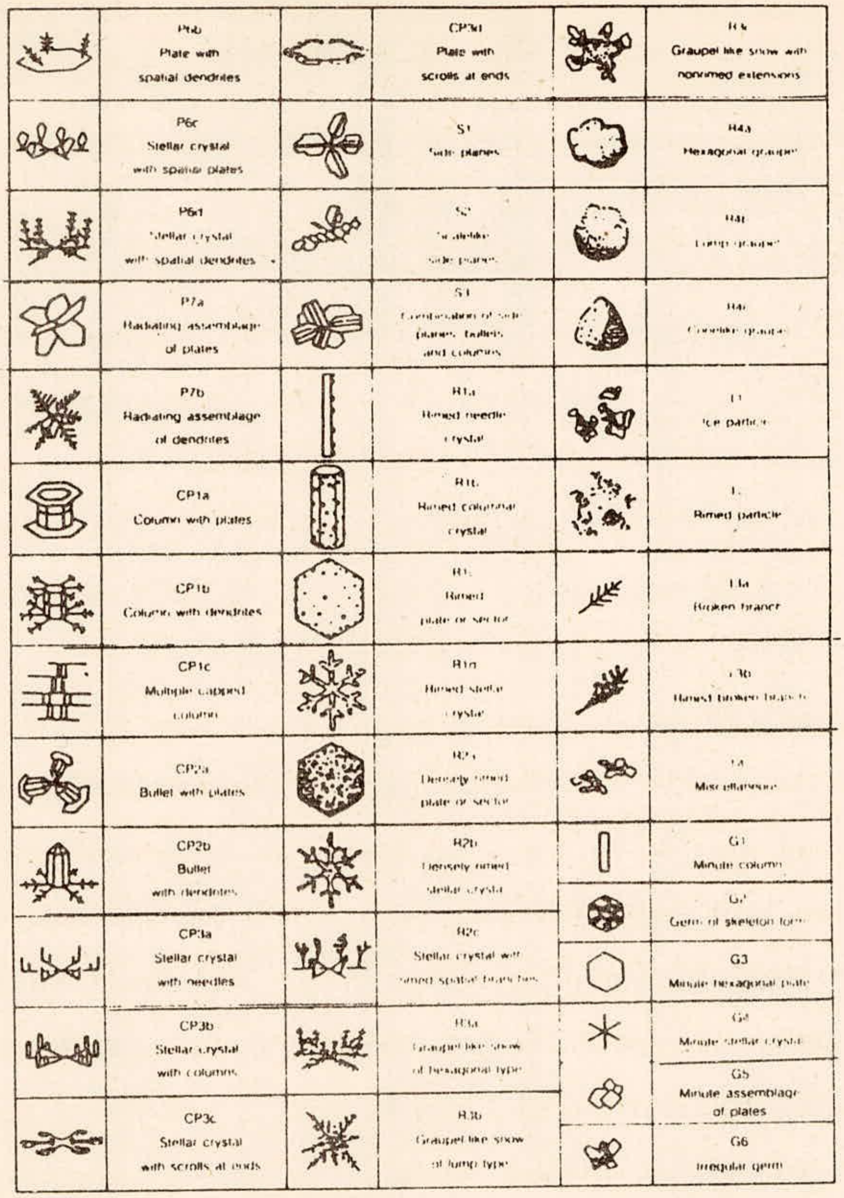


Fig. 2(b) Classification of natural snow crystals.

the light-reflecting properties of the snow surface are of particular importance. The capacity of bodies to reflect part of the incident radiant energy (direct and scattered solar radiation) is given by albedo (the ratio of reflected radiation to the total radiation falling on their surfaces):

The albedo of the surface of snow varies from 0.95 for pure freshly fallen snow to 0.20 for dirty snow saturated with water. Typical values of the albedo for pure snow are given below:

Fresh,dry,dazzling-white snow	0.90-0.85
Crystalline dry drift snow	0.80-0.70
Fine granular wet snow	0.65-0.55
Granular melting snow	0.55-0.45

The term of snow cover refers to the extent of ground area covered by the snow, whereas water equivalent of snow cover is the vertical depth of the water layer that would be obtained by melting the snow cover. Snow cover comprises the net accumulation of snow on the ground resulting from the precipitation deposited as snowfall, ice-pellets, frost, glaze ice and water from the rainfall much of which subsequently has frozen. The snow cover gradually built-up during the winter season and disappearing in the course of the following ablation season(early spring and late autumn) is known as seasonal snow cover. The structure of dimensions of snow cover varies both in space and time. The variability in the structure and dimension depends upon atmospheric wind, temperature and moisture of the air during snowfall and immediately after deposition. The temperature at the time of snowfall controls the dryness, hardness and crystalline form of the new snow and thereby its erodability by the wind.

The snow flakes undergo a rapid metamorphism after reaching the ground. This mechanism reduces their surface area and brings them to a more stable thermodynamic state. The introduction of the water in the form of either rain or surface melt causes a rapid metamorphism that eliminates the smaller particles to a more or less spheral shape. The initial state of the deposited snow depends upon the particular combination of wind condition and crystal type present during the deposition. At one extreme, aggregates of the dendritic crystals deposited during a calm can form a highly porous layer having a bulk density of about 10 kg/m^3. At other extreme, equidimensional aggregates of frozen water droplets or graupel can form a layer having a bulk density as higher as 500 kg/m^3, particularly if they have been distributed by surface winds during deposition. Bilello (1967) found that average snow cover density, ρ (kg/m^3) was related on a seasonal basis with average air temperature T(^{o}C) and wind velocity (m/s) by the following relation:

$$\rho = 152 - 0.31T + 1.9U \qquad ..(3)$$

Since T and U are partially controlled by the topography, large spatial variation in density are normal. This also indicates that blowing snow is the major mechanism for the redistribution of masses of deposited snow. Gray et al (1971) also reported for the Prairies, the density increases from 45 to 230 kg/m^3 within 24 hours due to wind action. Although initiated by wind action, this time densification of snow is also influenced by condensation, melting and other processes. Table 1 lists the densities of snow cover subjected to different levels of wind action. The nature and frequency of the parent storms and weather conditions during periods between storms also alter the structure, density and optical properties of snow due to variation in radioative exchange. The variation in snow density recorded at various depths of snow cover at Gulmarg (India) on 28 Feb.1976 are given in Table 1(b)

Further, because of the fractional drag extended on the air by the roughness of the land surface, the wind flow near the ground is normally turbulent and snow cover patterns reflect a resulting turbulent structure. Major deposition

Table 1(a)

DENSITIES OF SNOWCOVER

Snow Type	Density (kg/m^3)
Wild snow	10-30
Ordinary new snow immediately after falling in the still air	50 to 65
Setting snow	70 to 90
Very slightly toughened by wind immediately after falling	63 to 80
Average wind-toughened snow	280
Hard wind slab	350
New firm snow	400 to 550
Advanced firn snow	550 to 650
Thawing firn snow	600 to 700

TABLE 1(b)

Depth of Snow Cover (cm)	Density (gm/cc)
0	.120
50	.205
80	.235
110	.315
148 (ground level)	.330

(Reproduced from Upadhyay, 1981)

occurs in the areas located windward of zones with high aerodynamic roughness where the greatest deceleration in the wind speed occurs. Drifts are deepest where a long upstream fetch covered with loose snow has sustained strong winds from one direction. The drifts are less pronounced when winds change direction, especially at low speeds.

A unique phenomenon influencing the snow cover distribution within a forest is transport of intercepted snow. Wind causes a tree to vibrate, resulting with loosing and erosion of the intercepted snow, and the transport of the fragments down wind. Miller (1966) summerised the results from different studies of the transport processes. It was concluded that physical understanding of the process is complicated not only by the complexity of air flow patterns and velocity distributions within different forest covers but also by other factors including the manner in which snow accumulates, collects on and adheres to vegetation types, and cohesion and adhesion properties of snow. At present because of the lack of field measurements, the amount of snow transported by wind in a forest environment and the manner in which this snow affects the snow cover distribution is largely unknown.

2.2 Measurement of Snowfall

The problem of snowfall measurement has been recognised and investigated in several countries. Studies in Soviet Union(Struzer, 1965, 1969; Bogdanova, 1968; Kuzmin, 1975) and the United States (Larson, 1972; Hamon, 1973; Larson and Peck, 1974; Richard et al, 1974) were initiated to define the accuracy of snowfall measurements and to investigate and develop improved methods of measurements. Ferguson and Pollock (1971) and Harris and Carder (1974) reported discrepancies in snowfall totals obtained using different methods of measurement at the same station. In 1974, the World Meteorological Organisation (Commission for Instruments and Methods of Observation, CIMO), Working Group on the measurement of precipitation, evaporation, and soil moisture initiated a program to evaluate and test techniques for the measurement of snow fall using precipitation gauges. Goodison (1977) also described the methods of snowfall measurements.

2.2.1 Depth of snowfall

The snowfall is the amount of fresh snow deposited over a limited period (generally 24 hours) whereas the water equivalent of the fresh snowfall is the amount of liquid precipitation represented by that snowfall.

Direct measurements of fresh snow on open ground are made with a graduated ruler. To obtain a representative mean depth of the freshly fallen snow several vertical measurements are made in the places where snow has not drifted. The measurement of representative mean depth of new snow under drifting condition requires careful judgement by the observer. In such conditions. a large number of measurements should be made in both drifted and exposed areas. Special precautions are taken so as not to measure old snow. To ensure that old snow is not measured. the measurements are made on a patch or a snow board whose surface has been kept free of the snow before the snowfall. A snow board is a piece of plywood or light weight metal at least 40 cm by 40 cm, painted white or covered with white flannel, which provides a reference level for measurement. On a sloping surface(to be avoided if possible) measurements should still be made with measure rod vertical.

The depth of snow may also be measured in a fixed container of uniform cross-section after the snow has been levelled without compressing. The container is placed well above the average snow level, for example, at least 50 cm above the maximum observed level. and not exposed to drifting snow. The receiver is generally 20 cm in diameter and sufficiently deep to protect the catch from being blown out or else be fitted with a snow cross(i.e.two vertical partitions at right angles, subdividing it into quardants).

The measurements made by graduated ruler on snow boards are found fairly reliable provided that they are taken soon after each snowfall and that the snow on the board has not been subject to drifting, melting and evaporation or sublimiation.

2.3 Measurement of Snowfall Water Equivalent

The following methods are used to determine the water equivalent of snowfall:

2.3.1 Weighing or melting

This process is very simple. The cylindrical samples of fresh snow are taken with a suitable snow sampler and either weighed or melted. A repetition of this process at several points provides water equivalent of the snowfall.

2.3.2 Snow gauges

Snow gauges measure snowfall water equivalent directly. Essentially, any open cylinder in which snow can be accumulated and measured can serve as snow gauge. The gauges are divided into the following categories:

2.3.2.1 Non-recording snow gauges:

Standard gauges - The non-recording gauges generally consist of open receptacles with vertical sides, usually in the form of cylinders. Various sizes of orifice and height are used in different countries, and the measurements are therefore not strictly comparable. Snow collected in non-recording snow gauge is melted immediately and measured by means of an ordinary graduated measuring cylinder provided with the gauge. Gauges with limited capacity must be emptied frequently, usually once a day.

The standard gauge adopted for use in the United States consists of 20 cm cylindrical receptacle having a collector area of 325.16 cm^2. These gauges are used for both rainfall and snowfall measurements. In case of snowfall measurements, the funnel receiver and measuring tube are removed. The snow falling directly into the open cylinder, is melted and poured into graduated tube to measure the water equivalent of the snowfall. The cylinder is generally shielded to reduce wind turbulence around the orifice and is mounted high enough above the snow surface to minimise the accumulation of blowing snow into the gauge. Figure 3 shows various types of nonrecording snow gauges.

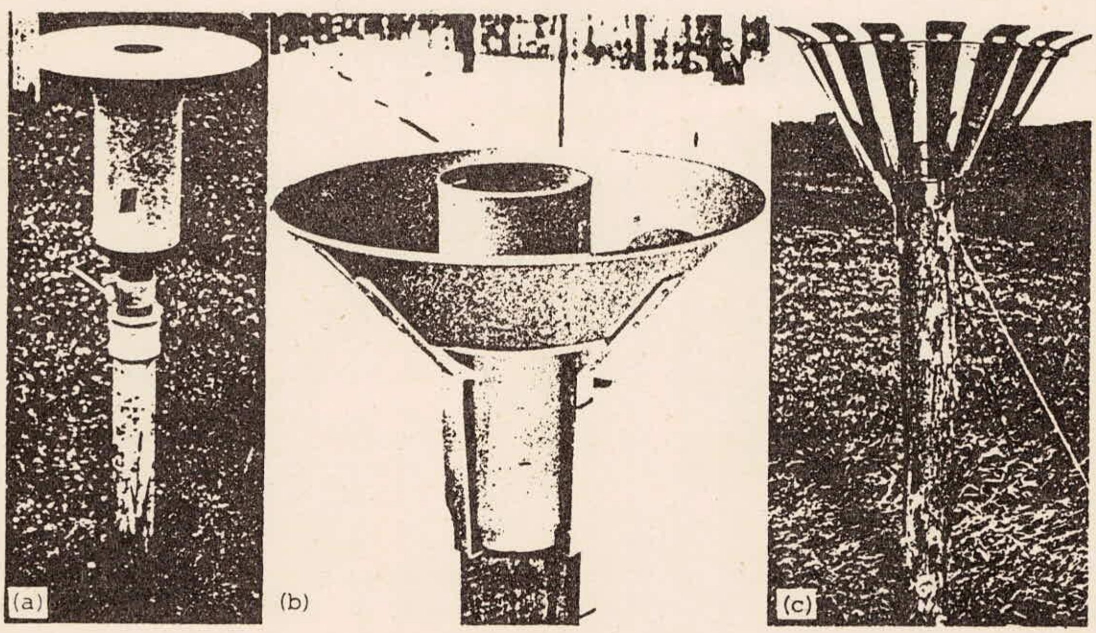


Fig.3 Types of non-recording gauges used to measure the water equivalent of snowfall.
(Reproduced from Gray and Male, 1931)

Shielded Nipher gauge:

The MSC Nipher Shielded snow gauge was designated as the official Canadian instrument in 1960. It has the shape of an inverted bell, and is usually constructed of spun aluminium of fiberglass. Wind tunnel tests conducted by Potter (1965) indicated that shield design is effective in minimising disturbances to the air flow over the gauge orifice. The collector, a hollow metal cylinder about 52 cm long, open at one end, and 12.7 cm in diameter, is placed inside the gauge so that its top rim is level with top edge of the shield. The gauge and shield are mounted on an adjustable stand, so that the lip of the shield can be maintained approximately 1.5 m above the snow surface (Meteorological Branch, Canada 1965). During periods of light winds snow may accumulate on the solid shield, while some may be blown into the collector by subsequent gusts of wind. Hence, the shield is cleared of snow after each observation. As the standard procedure, snow caught by this gauge is melted and measured in a special graduated glass to obtain the water equivalent. At present 14% of the 2500 precipitation stations in Canada are equipped with MSC Nipher Shielded snow gauge.

Some countries such as Sweden, the USA and the USSR have one national gauge for measuring both snowfall and rainfall. In winter the rainfall funnel of the gauge is removed so that snow enters directly into the collector.

Storage gauges:

Storage gauges are used to measure total seasonal water equivalent of the snowfall in remote, sparsely inhabited areas where daily observations are impractical. Storage gauges have large capacities to store snowfall water equivalent during periods as long as a year. In areas where extremely heavy snowfall occurs, the collector is placed above the maximum expected depth of snow cover. This may be accomplished by mounting the entire gauge on a tower or by mounting the collector on a stand pipe used to store the catch.

Storage gauges are monitored manually at regular or irregular intervals depending upon the accessibility of the site. The typical gauge consists of a vertical 30 cm diameter steel pipe of sufficient length to place its 20 cm catch ring above maximum accumulated snow. The criteria for exposure and shields for these is also same as in other gauges.

An antifreeze solution is placed in the receiver to convert the snow which falls into the gauge to the liquid state. Moreover, the solution also prevents the freezing of water in the collector. The amount of antifreeze required depends on the expected amount of snowfall and the minimum temperature expected at the time of maximum dilution. An ethylene glycol water solution is commonly used as the antifreeze. However, since glycol is denser than water, a problem arises with the mixture if it is not stirred periodically to prevent freezing. Mayo (1972) recommended the use of an antifreeze solution of 40% ethylene glycol and 60% methyl alcohol by volume. Moreover, a mixture of 37.5% water by weight has also been recommended by WMO (1981). However, the use of an ethylene glycol solution is also suggested as an alternate. The volume of the solution placed in the receiver is preferred to exceed one-third the total volume of the gauge. In a storage gauge it is important that a slush layer, which may solidify in very cold weather, not be permitted to form in the collector. Poor mixing of precipitation (snowfall) and antifreeze, leading to the formation of slush layer, can be prevented by using inexpensive nitrogen gas bubblers or a self-mixing anti-freeze solution.

An oil film is used in the gauges to prevent losses of water and antifreeze by evaporation. An oil film about 8 mm thick is sufficient to minimize the evaporation from the gauge. Low viscocity, non-detergent motor oils are used for covering layer of the mixture. However, transformer and silicone oils have also been found suitable.

The total snow catch water equivalent is determined by weighing or measuring the volume of the contents of the receiver. The usual practice is to read the vertical depth of the fluid with a ruler. The water equivalent in the gauge is calculated from the liquid depth and the density of the antifreeze mixture. The Sacramento storage gauge which is commonly used to measure the water equivalent in the mountainous regions of Canada characterized by heavy snow fall is shown in Fig.4. It is cone shaped with length of about 120 cm and has a 20.3 cm orifice and a maximum capacity of 2540 mm water equivalent. In low snowfall regions smaller stand pipe storage gauges could be used. A storage gauge can be modified for telemetering by connecting it to a stilling well enclosed in an adjacent shelter. A float activated, parallel digital recorder could be used to monitor the depth of fluid in the stand pipe and provide input to a telemetry system. This type of gauge is referred to as a float type gauge.

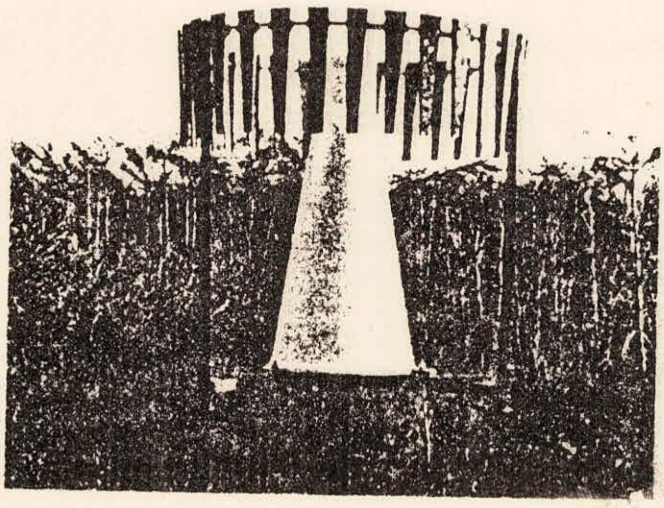


Fig.4 Sacramento storage snow gauge

2.3.2.2 Recording snow gauges:

The recording gauges are designed for use in locations where a continuous record is desired and for locations where the gauge can not be regularly attended by the observer. The following snow gauses are used for this purpose.

Weighing type snow gauge:

In these instruments the weight of catch bucket plus the snowfall accumulating in it is recorded continuously, either by means of a spring mechanism or with a system of balance weights. The spring compresses after accumulation of catch in the bucket and activates a recording mechanism, usually a pen, to produce a trace on a chart. The mechanical displacement of the spring can be converted to a digital output signal which can be recorded in situ or telemetered by any device to the required destination. This type of gauge normally has no provision for emptying itself but by a system of levers it is possible to make the pen traverse the chart any number of times. The capacities of weighing type gauges range from 300-600 mm water equivalent. The time resolution capabilities can vary from 5 min to several hours. However, the capacity, time resolution and the duration of operation are closely interrelated characteristics which must be considered when selecting a gauge to satisfy specific study requirements. Addition of the oil and antifreeze solution to the receiving bucket enable this type of gauge to record volumes and rate of precipitation for long periods of time, limited only by the necessity of periodic changing of the recording charts and emptying the receptacle. The main advantage of this type of instrument is its capability to record snow, hail and mixture of snow and rain. It does not require the solid precipitation to be melted before it can be recorded.

Weighing type gauges are equipped with shields to reduce the wind turbulence over the gauge orifice.Alter shield consisting of a number of slats mounted to surround the orifice of gauge is found adaptable for long duration recording gauges. In very windy and unprotected sites, the slats are sometimes bridled or joined to each other by a light chain to prevent them looping on the ring thereby increasing turbulence. In sheltered sites the slats are left free swinging because if they are bridled snow may collect between the gauge and the lower end of the slats and then accumulate on this base to cover the orifice. The shield is attached such that it extends 1.25 cm above the rim of the orifice. However, the height at which orifice is mounted differs from country to country, but the common height is 2 m above the ground level. In regions of the high snowfall it is recommended that the gauge could be mounted so that its orifice remains at least 1 m above the surface of maximum expected snow pack.

The two most common weighing type snow gauges namely Universal snow gauge and Fischer and Porter Snow gauge are shown in Fig.5 and Fig.6. respectively.

The float gauges are found unsatisfactory because heat required to melt the snow as it falls set up vertical currents above the gauge opening and causes excessive evaporation losses. Similarly in the tipping bucket gauge also snow must be melted by heating the gauge, which leads to increased evaporation- and thus less catch of snow compared to manual measurements. Also, the heating systems usually requires electric power at the measuring site. An improved design of recording snow gauge is also suggested by Jairell(1975).

Vibrating wire strain gauge:

The Norwegian Geotechnical Institute (NGI), has recently developed and tested a new automatic snow gauge which can measure accumulated precipitation with a resolution better than 0.1 mm (Bakkehoi et al. 1985). The gauge is a direct weighing device and is based on the use of vibrating wire strain gauge. The principle sketch of the system is shown in Fig.7.

In the prototype version, the snow gauge is suspended from three small steel wires, each of which is in effect the sensing element in a vibrating wire type strain gauge. When gauge wires are set into vibration by an electromagnetic exciter, their resonant frequency of vibration is proportional to the square of the tension in the wire. This change in the frequency signals is a measure

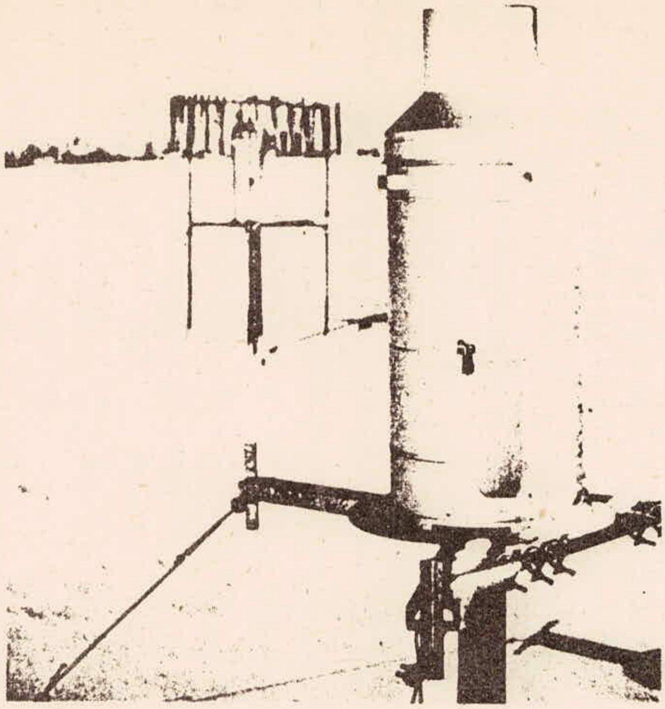


Fig.5 Universal snow gauge
(Reproduced from Gray and Male, 1981)

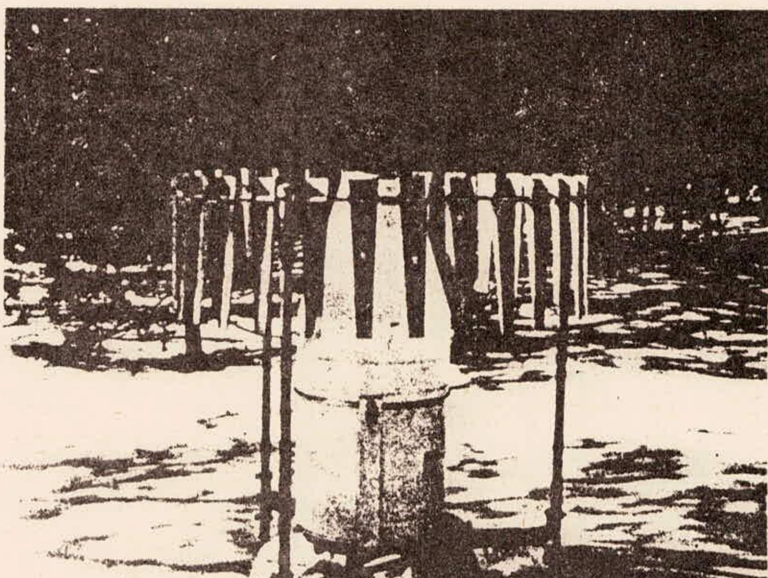


Fig.6 Fischer and Porter snow gauge with Alter Shield
(Reproduced from Gray and Male, 1981)

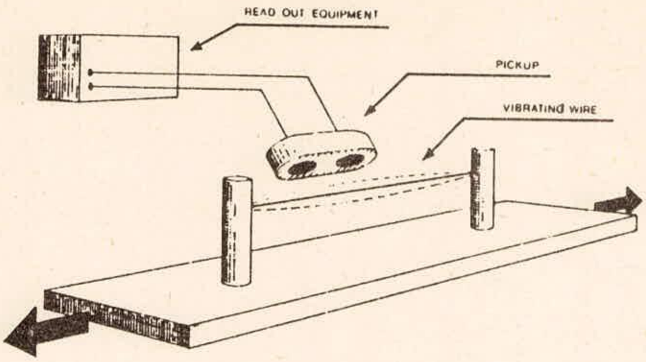


Fig.7 - Principle of the Vibrating Wire Gauge
(Reproduced from Bakkehoi et al, 1985)

Fig 8- Geonor Version of Vibrating Wire Strain Recording Gauge
(Reproduced from Bakkehoi et al. 1985)

of the change in tension in the wires and correspondingly a measure of accumulative weight of precipiration in the container.

In the new version of the gauge one vibrating wire sensor is used as one of the supports provided the gauge is carefully levelled to ensure equal load distribution (Fig.8). The gauge itself contains two electromagnets, one of these magnets is the exciter, the other is to pick-up. When the wire is forced to oscillate, an alternating current is induced in second electromagnet which has the same frequency as the natural frequency of vibration of gauge wire. This signal, when amplified, provides a measures quantity which can be readily determined.

The advantage of this system is a high resolution and accuracy, and as it is a frequency that is measured, a cable of more than one kilometer's length can be used from gauge to the reading equipment. The system can operate continuously or be read at certain intervals. NGI's prototype instrument has capacity of upto 300 mm -600 mm (Bakkehoi et al, 1985).

2.3.2.3 Snowfall water equivalent by depth measurements

The water equivalent of fresh snowfall from depth measurements is obtained using an appropriate relationship. Commonly, the average density of freshly fallen snow is accepted as 100 kg/m^3, that is, 1 cm of snow is considered equal to 1 mm water. This relationship is valid only for long term average. Appreciable error in the snowfall water equivalent estimates can also result by assuming that freshly fallen snow has a density of 100 kg/m^3. Such deviations observed and estimated water equivalent has been illustrated in Table 2. The density of fresh snow exhibits wide temporal and spatial variations, and is primarily controlled by the amount of air in the interstices between individual snow crystals. The air space is a function of type of snowfall and its crystal structure, the meteorological conditions(especially, upper air temperature, and wind speed

TABLE-2 : Comparison of measured snowfall water equivalent with the estimated using a mean density of 100 kg/m³ (Male and Gray, 1981)

Hour	Accumulated Storm Board Depth cm	Measured Water Equivalent mm	Estimated Water Equivalent mm	(Estimated - Measured) as a Percentage of Measured %
1	1.5	0.89	1.5	+68.5
2	3.3	2.26	3.3	+46.0
3	4.4	3.86	4.4	+14.0
4	5.2	5.69	5.2	- 8.6
5	7.2	8.73	7.2	-17.5
6	9.5	11.00	9.5	-13.6
7	9.8	12.57	9.8	-22.0
8	11.8	16.13	11.8	-26.8
9	12.0	17.09	12.0	-29.8

and direction near the surface) prevailing during and immediately following the snowfall, the elapsed time of measurement of snowfall after the beginning or end of the storm, the siting if easurement station and observer bias.

Studies based on data at CSSL indicate that a fair relationship exists between surface air temperature and density of freshly fallen snow (Diamond and Lowry, 1953). Figure 9 shows the plot of their data relating density of new snow with surface air temperature. An increase in density of 0.0036 g/cc per

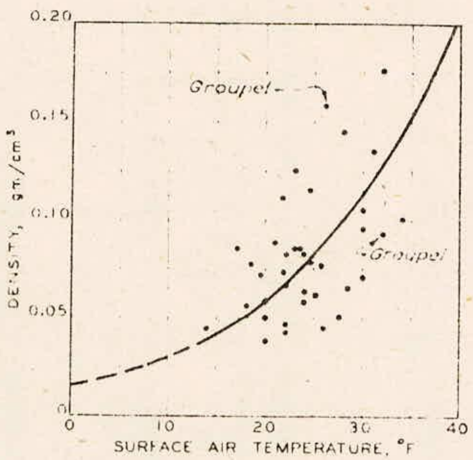


Fig.9 Variation in density of new fallen snow with temperature

degree F was found by their observations. Rikher (1954) reported densities of new fallen snow varying with surface wind. and ranging from .06 units for calm conditions to 0.34 units for snow deposited during gale winds. Moreover. densification of a fresh snowfall may occur rapidly such that water equivalent estimates. based on initial density of snowfall and depth measurement taken only a few hours after a storm. can be quite erroneous. Table 3 shows the temporal variation in snowfall density at a sheltered site.

TABLE 3- Changes in density of freshly fallen snow on the ground after cessation of snowfall

Time[a]	Measured Depth cm	Density kg/m^3	Measured Water Equivalent[b] mm	Water Equivalent Using 100 kg/m^3 mm
1030	8.7	104	9.06	8.70
1315	7.0	131	9.14	7.00
1700	6.0	152	9.09	6.00

[a] General climatic conditions during the day: cloudy, maximum temperature 1°C, wind speed ~ 6 m/s.

[b] Determined by clearing an individual 930 cm^2 snow board.

Further, the snowfalls in different geographic and/or climatic regions also have different densities. Gray et al (1970) measured average densities for freshly fallen snow of 45 kg/m^3 during non-drifting conditions and 230 kg/m^3 for drifted snow a day later, during blizzard conditions, a six fold increase in density caused by drifting had occurred within a period of less than 24 hours. Rockie et al (1974) reported the mean new snow densities of 77 to 101 kg/m^3. The fresh snow density in the central and western Himalayas in India has been reported from 140 kg/m^3 to 100 kg/m^3 (Rangachary and Tej Ram, 1983). These figures show that a mean density factor would underestimate or overestimate the snowfall water equivalent in many regions.

Upadhyay (1981) established a relation between fresh snow fall density (ρ , gm/cm^3), and ambient temperature T (°C) in snow bound areas of northwest Kashmir. For this purpose the observations were made at three stations from 1973-1977. The worked out linear regression equations between ρ and T are given below:

$$\rho_1 = 0.123 + 0.005\ T$$

$$\rho_2 = 0.107 + 0.003\ T$$

$$\rho_3 = 0.117 + 0.008\ T$$

2.4 Errors in Snowfall Measurement:

A large number of studies have been conducted to investigate the source of error in the snowfall depth and water equivalent measurements. Errors in the ruler measurement of snowfall depth mainly originate from poor siting i.e. an open site susceptible to drifting snow and from observers bias. The type and magnitude of error may vary from storm to storm, observer to observer and station to station.

Errors in the measurement associated with non-recording gauges are attributable to the effect of wind speed on gauge catch and evaporation, spillage, wetting and retention losses. The last type of loss results from the water retained on the walls of the measuring cylinder by surface tension. Goodison (1978b) reported a mean retention loss of 0.15 ± 0.10 mm for each Nipher shielded gauge.

The error in the measurement of water equivalent of snowfall by the gauges is also obtained due to poor designing of the gauge. The construction of the aperture is made such that accumulation of wet snow about the rim will be minimum. Moreover, collector also is preferred to store one day's snowfall: this is also important in order to avoid the drifting of the caught snow out of the collector. In the weighing type recording gauges errors are obtained due to oscillation of balance in strong winds. However, fitting of an oil damping mechanism reduced this error completely. For a gauge read daily total losses should be less than 0.25 mm. A regular testing of all gauges is needed for the possible leaks.

2.5 Shielding of the Snow Gauges

Precipitation in the form of snow is much more subject to adverse wind effects than is rainfall. Many investigators(Weiss and Wilson, 1957; Struzer, 1965; Hamon, 1973; Larson and Peck, 1974; Goodison, 1978a) indicate that wind is the major cause of error in snow gauge measurements. In exceptionally windy locations, the catch in a gauge with or without a wind shield may be less than half the 'true' snowfall. Therefore, sites selected for measurements of snowfall and/or snow cover are recommended, as far as possible, in areas sheltered from the wind(WMO. 1971). The undercatch by any gauge because of wind is related to three factors: the wind speed and its vertical profile, the buoyancy of the particles. and the obstruction of the gauge to the airflow.

Figure 10 shows the diagram used to illustrate the effect of introducing a gauge into a horizontal wind field with the resultant in wind speed over the orifice of the gauge. The snow particles are assumed to be deflected, and the amount of snow entering the gauge is less than the amount that would have passed through the same horizontal area if the gauge had not been placed in the wind field. Figure 10(a) and (b) show that turbulence induced by roughness in the area of the gauge can result in increased upflow or actual downflow over the orifice in comparison to flow shown in Fig.10(a). The variation in the flow depends on many factors such as the location and direction of the roughness elements in relation to gauge, the wind direction, the wind speed. the stability of the air. and the vertical wind movement associated with falling snowfall.

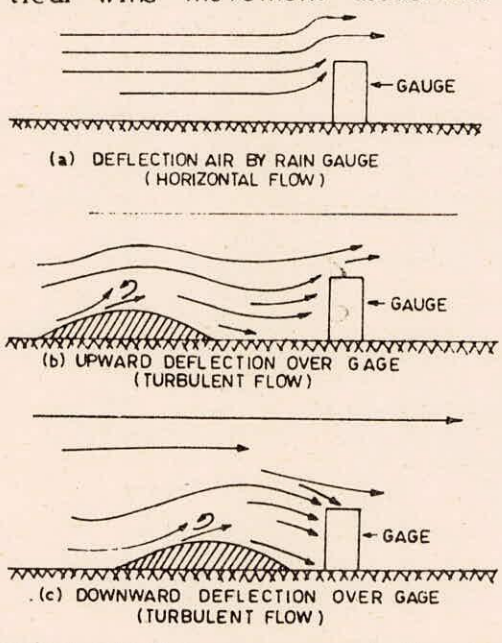


Fig.10 Variation airflow over precipitation gauge

Figure 11 illustrates the airflow over an unshielded cylinder of Nipher gauge. Wind shields attached to the gauges have been shown to be quite effective in reducing snow catch errors due to wind. However, no shield yet developed to eliminate wind-cause measurement errors. entirely in the strong winds.

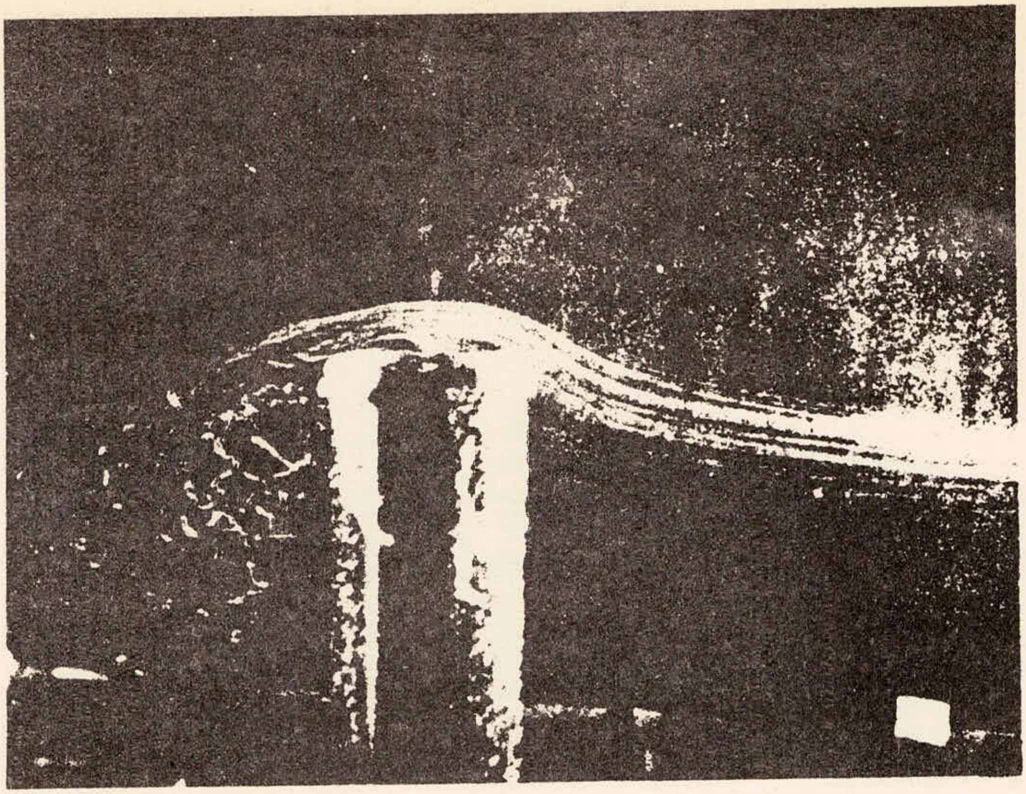


Fig. 11 Airflow pattern over an open cylinder
(Reproduced from Gray & Male, 1981)

In areas where suitable gauge locations are not available, either the dual gauge approach or the dual circular snow fence shield (Fig.12, 13 and 14) is preferred to the installation of a single exposed gauge. In the dual gauge system, the wind movement on a pair of adjacent shielded and unshielded gauges is assumed to be equal and, therefore, the true snowfall can be computed, using a relation involving the ratio of catches of the two gauges and the catch in the unshielded gauge. An empirical method for calculating the true amount of snowfall using measurements from a dual gauge arrangement has been suggested by Hamon (1973). The procedure assumed that following relationship exists between the catches of an unshielded gauge P_u and a shielded gauge P_s and the actual snowfall P_a:

$$\ln (P_u/P_a) = B \ln (P_u/P_s) \quad ..(4)$$

where, B is a calibration coefficient whose magnitude is dependent on gauge type, but essentially independent of wind speed and type of precipitation. Canadian research has also indicated the dependence of B on air temperature. A study conducted in South-Western Idaho showed that the value of B for the Universal

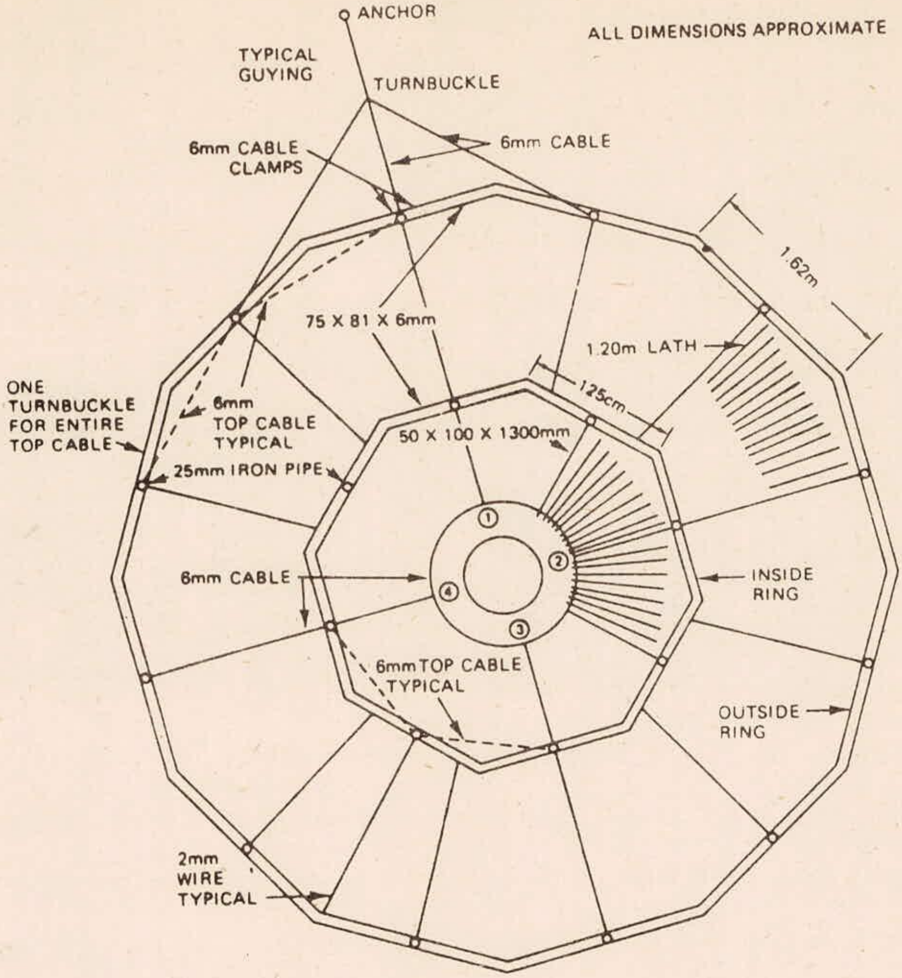


Fig.12 Plan view of dual circular snow fence
(Reproduced from W.M.O., 1981)

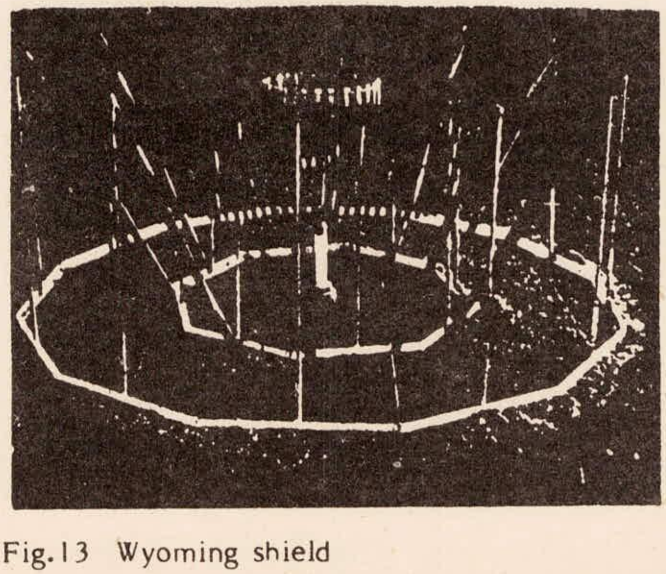


Fig.13 Wyoming shield
(Reproduced from Gray & Male , 1981)

gauge using a rigid, bridled. Alter shield was 1.70. This technique has the advantage in that the reduction in catch by wind is used to advantage instead of being the cause of the major source of error.

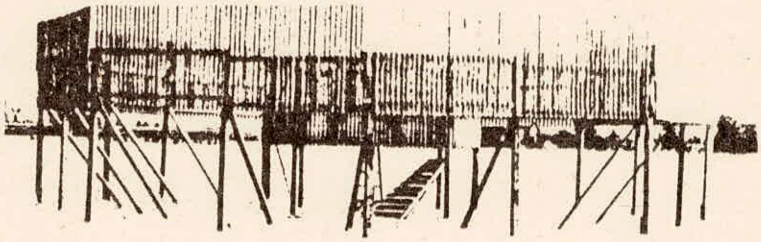


Fig.14 Dual snow fence used with the Tretyakov gauge
(Reproduced from Gray & Male , 1981)

The dual circular snow fence shield installation is essentially by the construction of a suitably protected gauge site through the use of snow fences. Two concentric rings of 50% porosity fences are constructed with the outer ring having a radius of 3 m and the inner ring a radius of 1.5 m. The outer ring is inclined at 30^{o} and inner ring at 45^{o} to the vertical. The gauge is installed in the centre of rings with a clear space of about 1.5 m below both the fencing and gauge. This configuration allows the horizontal wind to be deflected down and under the gauge thereby reducing turbulence at the gauge orifice. The inner ring of fencing is approximately 30 cm higher than the gauge orifice and the outer ring is about 60 cm higher than the gauge orifice. However, its physical size may be a constraint at some locations and its installation is more time consuming and difficult. Richard et al (1974) reported that on the average catch of the gauge equipped with dual circular snow fence shield, well known as 'Wyoming Shield' could be within 10% of that recorded by a standard gauge in a smallest forest opening.

A double fence shield for snow gauges has been developed and tested in the USSR. The installation is equipped with two fences, each having 1.5 m slats at porosity of 50%, mounted vertically at radii of 2 m and 6 m around the gauge.

The orifice of the gauge is set at a height of 3 m. the bottom of the outer fence at a height of 2m. and of the inner fence at a height of about 1.5m above the ground. This arrangement of fences prevents accumulation of drifts. For wind speeds between 3 and 6 m/s. the catch ratio of the shielded gauge ranged from 99 to 92% compared with 70 to 40% for a standard installation.

Larson and Peck (1974) studied the catch efficiency of the shielded and unshielded gauges. The results obtained are shown in Fig.15. The values of 'true catch' were determined from the measurements by similar gauges located in a nearby sheltered site. The results show that deficiency increases non linearly with wind speed and that shielded gauges catch more than unshielded gauges. This relation is also a function of location and measurement period: the differences reflect the integrated effect of gauge exposure and other meteorological elements on gauge catch. The comparison of precipitation gauge catches with a modified Alter and rigid Alter type wind shields has been reported by Rawls etal(1975)

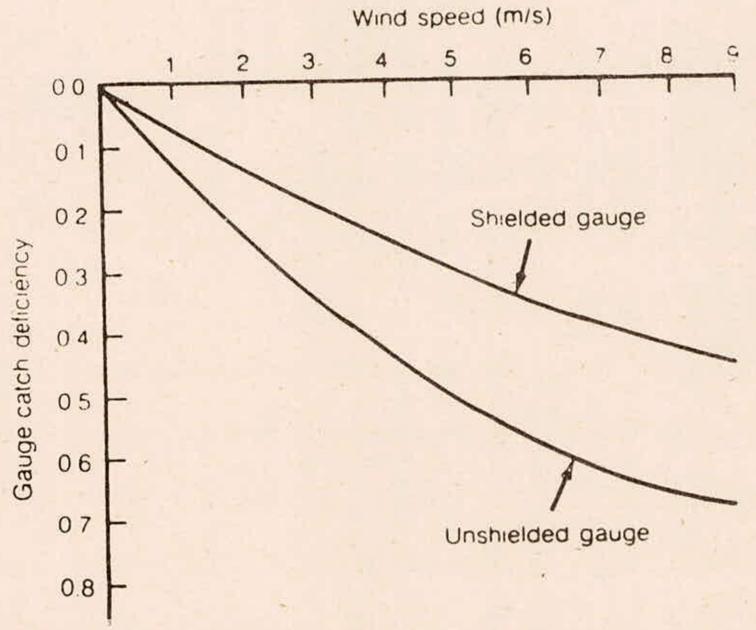


Fig.15 - Mean Gauge Catch deficiency of shielded and unshielded gauges for snow as a function of wind speed.(Gray & Male, 1981).

2.6 COMPARISON OF SNOW GAUGE MEASUREMENTS

Ideally. each point measurement should provide a true snowfall total. but this is not the case. Environment and physical parameters such as wind speed.

air temperature, site exposure and gauge configuration interact to cause the point measurement to deviate from the true value. Long term observations of the catchments of the catches of different gauge types at the same site provide basic comparative data. The greater variations in snow catch as compared to rain, has been found (Allis et al, 1963). Harris and Carder (1974) reported from a ten year study conducted at Beaverlodge, Alberta, that over a wide range of snowfall amounts the snow water equivalent totals recorded by the MSC Nipher gauge were consistently larger than those measured by a United States Weather Bureau (USWB) gauge equipped with an Alter shield. In 567 comparative observations, the USWB gauge recorded smaller amounts in 95% of the cases and larger amounts in only 5% comparative observations.

Goodison (1977) made comparisons of the snowfall catches by different snow gauges to the ground snow water equivalent and snow boards (Table 4). It was reported that MSC Nipher shielded snow gauge gave better estimates of snowfall water equivalent than other gauges. Further, field tests (Goodison, 1978a) and wind tunnel flow visualization experiments indicated that the MSC Nipher shielded gauge has a superior catch efficiency for measuring snowfall water equivalent compared to standard Alter shielded recording gauges. However, in low snow fall regions, such as the Arctic and Prairies, the MSC Nipher gauge has been found to be less efficient because retention losses and trace amounts were not being accumulated (Goodison, 1978b). A recording gauge would be more desirable for operation in such regions.

The recording gauges with the new Nipher shield recorded a substantially higher catch than Alter shielded, unshielded, or Wyoming shielded gauge, but the catch was still 7-15% less than the standard MSC Nipher gauge at the station (Table 5). Data from Saskatchewan for the 1979-80 winter confirmed the higher catch efficiency for recording gauges using the Nipher type shield. A Nipher shielded Fischer and Porter caught 96% of the standard MSC Nipher

TABLE 4

Mean ratio of gauge catch to ground 'true' measurement 1974-76 for MSC Nipher shielded, Fischer and Porter recording Universal recording and Tretyakov shielded gauges (Goodison, 1977).

Gauge Description[b]	Site Description	Mean Ratio[c] (gauge/snow board)	Mean wind speed[d] m/s
Snow Board on Ground	Sheltered	1.00	---
MSC Nipher Shielded	Bush-sheltered	1.01	0.48
MSC Nipher Shielded	Valley-sheltered	1.05	1.74
MSC Nipher Shielded	Open-plateau	0.94	3.80
MSC Nipher Shielded	Open-flat	0.91	3.95
12.5 - cm snow collector (no Nipher shield)	Open-flat	0.48	3.95
Fischer and Porter c/w[e] Free Swinging Alter Shield	Bush	0.96	0.48
Fischer and Porter c/w Free Swinging Alter Shield	Valley	0.86	1.74
Fischer and Porter c/w Free Swinging Alter Shield	Plateau	0.51	3.80
Fischer and Porter c/w Free Swinging Alter Shield	Flat	0.47	3.95
Fischer and Porter - unshielded	Plateau	0.32	3.80
USSR Tretyakov Shielded	Flat	0.57	4.24
Universal Recording c/w Free Swinging Alter Shield	Flat	0.58	3.95
Universal Recording - unshielded	Flat	0.37	3.95

[a] Results are means of values obtained from data collected during snowstorms, irrespective of wind speed or temperature, as measured at Cold Creek Hydrometeorological Research Station, Bolton, Ontario.

[b] All gauges mounted at 2 m.

[c] Mean ratio of gauge catch to ground catch measured on a snow board at a sheltered site.

[d] Mean wind during snowstorms, measured at each site at 2 m above ground.

[e] c/w complete with

compared to only 37% for an Alter-shielded Fischer and Porter recording gauge(Table 6).

Figure 16 shows the mean ratios of the gauge catch to ground true value (as measured on snow boards in a sheltered site) as a function of wind speed for selected shield gauges. It has been noted that all ratios except that for the MSC Nipher shielded gauge decrease with increasing wind speed.

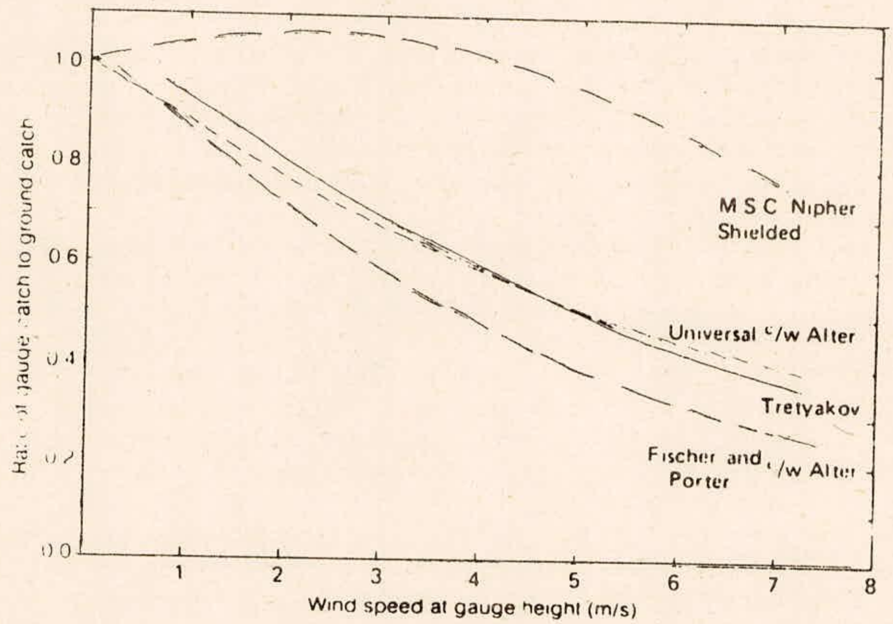


Fig.16 Relationship between gauge catch and ground catch as a function of wind speed for different types of gauges.

The Nipher shield minimises disturbance of the airflow over the gauge and eliminates updrafts over the orifice which result in an improved catch.

2.7 AREAL MEASUREMENT OF SNOWFALL

The absolute point value of the snowfall depth is representative of depth on a very limited area. The size of the area depends on the accumulation period, physiographic homogeneity of the area and the topography of the area. Point snowfall observations may be used for larger areas when the accumulation period is long, the terrain is flat, the snowfall is steady and major redistribution by wind does not occur. Until new techniques for measuring areal snowfall are fully developed and tested, point snowfall measurement will remain the primary source of data. To obtain reliable estimates of spatial distribution of snowfall, the consideration must be given to net work design. As mentioned earlier, the accuracy of mean areal snowfall is also a function of the period of accumulation. Figure 17 shows the change in the absolute error of areal winter precipitation for different network densities expressed as the percentage of the value obtained with a station density of eight gauges per 25,000 km^2. It is shown that the absolute error in mean areal snowfall measurements decrease with an increase in network density or period of accumulation (Gray and Male, 1981).

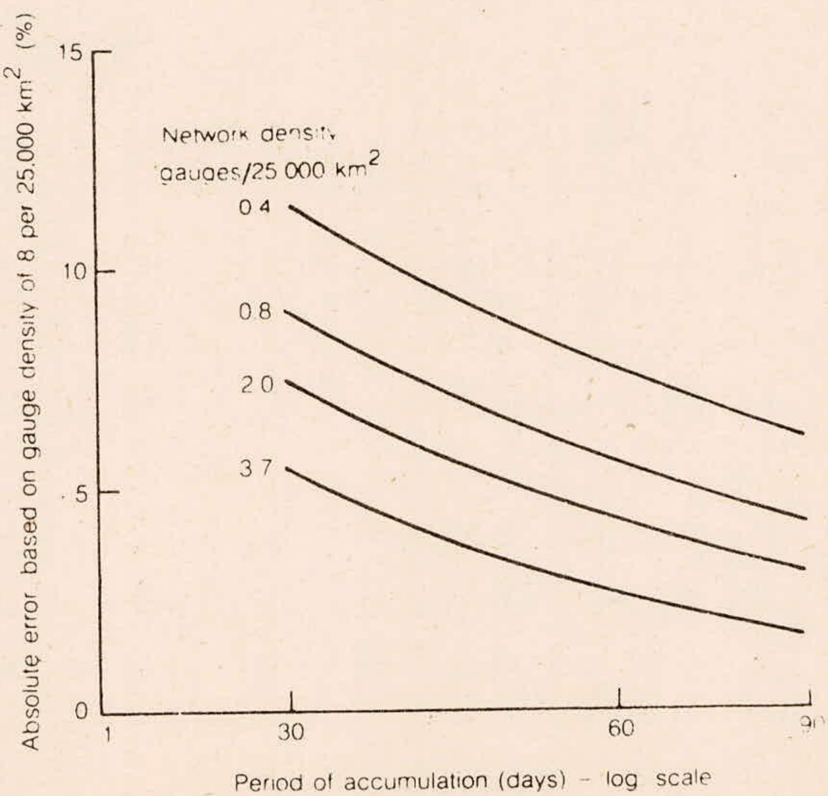


Fig.17 Average error of estimated areal winter precipitation over Saskatchewan, expressed as a percentage of the value obtained with a network density of 8 gauges per 25,000 km^2.

TABLE 5

TESTING OF MSC NIPHER SHIELDS FOR RECORDING PRECIPITATION GAUGE 1978-79 SNOW SEASON

Precipitation	Wyoming Belfort Ga. (mm)	Nipher F-P	Nipher Bel.	Nipher F-P (mm)	Alter Shielded Belfort(mm)	Unshielded Belfort(mm)	MSC Nipher(mm)
Jan.13,14,79 (snow & rain)	18.3	30.3	21.6	12.7	13.5	11.2	21.8
Jan.17/79	7.1	7.6	8.9	2.5	4.6	2.5	9.1
Jan 20,21/79	5.6	5.1	7.1	2.5	3.8	2.0	7.6
Jan.24,25/79 (snow & rain)	21.8	30.5	35.3	22.9	25.4	24.6	33.0
Feb.4/79	2.0	2.5	2.5	2.5	2.0	1.5	4.0
Feb.7,8/79	3.0	2.5	3.6	2.5	2.0	1.0	1.8
Feb.16/79	1.3	2.5	1.5	Nil	0.8	0.3	1.8
Feb.21/79 (rain)	1.0	2.5	1.0	2.5	0.8	0.5	1.3
Feb.21/79 (rain)	1.0	2.5	1.0	2.5	0.8	0.5	1.3
Feb.23,24/79 (rain)	8.9	7.6	6.9	10.2	10.2	9.9	10.9
Feb.26/79	3.8	5.1	5.3	2.5	2.3	1.0	8.1
TOTALS	72.8	86.2	94.2	60.8	65.4	54.5	101.4
CATCH TOTAL	72%	85%	93%	60%	65%	54%	

* F-P FISCHER-PORTER PRECIPITATION GAUGE

TABLE 6: SNOW GAUGE CATCH COMPARISONS, BAD LAKE, SASK. 1980

MONTH	FISCHER-PORTER ALTER SHIELDED	FISCHER-PORTER NIPHER SHIELDED	MSC NIPHER SHIELDED SNOW GAUGE
FEBRUARY	2.5mm	10.2mm	12.8mm
MARCH	5.1mm	5.1mm	6.2mm
APRIL	5.1mm	17.8mm	15.6mm
TOTAL	12.7 mm	33.1mm	34.6mm
CATCH TOTAL AS % OF STANDARD NIPHER	37%	96%	

Efforts have also been made to measure the spatial distribution of snowfall by radar. Wilson (1974) reported that radar can be used for estimating the snowfall water equivalent with approximately same accuracy as that for measuring rainfall, provided an empirically derived range correction is applied to the radar estimates. A study conducted to measure snowfall by radar showed that for radar ranges of less than 50 km. 80 to 90% of the radar estimates were within a factor of two of the gauge measurements (Wilson, 1975). Ohtake and Henmi (1970) reported that the Z-R relation (between the reflectivity of the snowflakes Z measured by the radar and the rate of snowfall R) varies with crystal type. Table 7. illustrates the relation between Z-R for different crystal forms. In case, the information about the snowflake crystals in a particular storms is not available, the relation $Z = 1780\ R^{2.21}$ has been found to be applicable (Sekhon and Srivastava, 1970). Puhakka (1975) suggested that the mean surface temperature is also a factor affecting the reliability of the radar measurements of estimating snowfall (Table 7).

TABLE 7 Z-R relations for different crystal forms (Reproduced from Puhakka, 1975)

Hail	$Z = 320\ R^{1.6}$
Graupel	$Z = 900\ R^{1.6}$
Snowflakes (Ohtake and Henmi, 1970)	
plates and columns	$Z = 400\ R^{1.6}$
needle crystals	$Z = 930\ R^{1.8}$
stellar crystals	$Z = 1800\ R^{1.5}$
spatial dendrites	$Z = 3300\ R^{1.7}$
Snow (Puhakka, 1975)	
Dry ($\bar{T} < 0°C$)[a]	$Z = 1050\ R^{2}$
Wet ($\bar{T} > 0°C$)	$Z = 1600\ R^{2}$

[a] $\bar{T}$ = mean air temperature

2.8 DEPTH AND EXTENT OF SNOW COVER

2.8.1 Snow Stakes

The most common method for determining the depth of snow accumulation is by means of a calibrated stake fixed at a representative site which can be easily inspected from a distance. The entire length of the stake are graduated in meters and centimeters. The stakes are painted white to minimize undue melting of snow immediately surrounding them. In inaccessible areas, stakes are provided with cross bars so that they can be read from a distance with the aid of field glasses, telescopes or air-craft.

An estimate of the water equivalent is also possible by using density data from nearby (within 40 km) course located at similar elevation and those having similar conditions of environment (Gray and Male, 1981). To reduce the cost of extensive field sampling for obtaining mean depths in a forest, a simulation model has been developed by Woo and Steer(1986).

2.8.2 Optical Snow Depthmeter

An optical snow depth meter was conceived as an automatic means to obtain snow depth for unmanned stations(Mizuno, 1965, 1971; Dirmhrin and Craw (1971). The snow depth meter discussed by Dirmhrin and Craw (1971) consisted of sensors of a light source and a number of equally spaced photocells arranged vertically(Fig.18) Snow depth is indicated by the number of cells not activated by the light source at a given time, and this number can be determined by examining a graphical recorder trace or by counting the signals transmitted by a telemetering device. The measurements are determined by the vertical spacing of the photocells. The only limiting factor is the size of the cells themselves. If 5 by 5 mm silicon cells are used with no space between two adjacent cells, the accuracy of the recorded depth will be about 1/8 inch.

Tsuda and Uotsu(1972) developed a two-pole type snow depth-meter in which snow depth is measured by a xenon flash light beam ascending between two poles (Fig.19).A light projecting pole and a light-receiving pole are set up in which silts are open face to face. The light source and the detector capsules are usually rest under the earth surface in different poles.At the time of observation, they will ascend from the rest position of the poles simul-

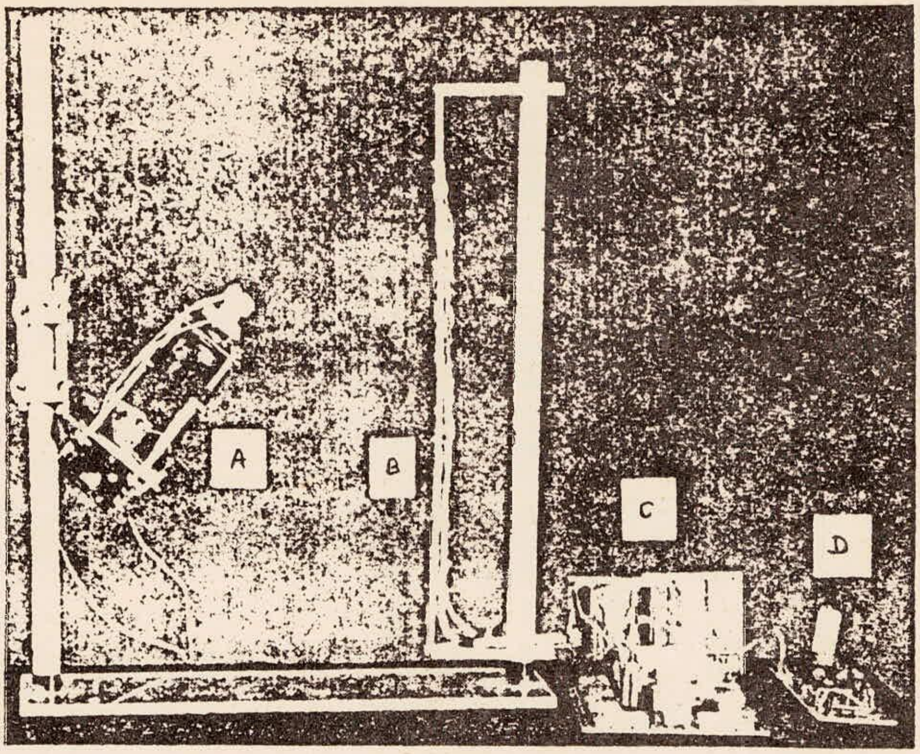


Fig.18 Components of the snow-depth indicator : A-light source; B-photocell ladder: C-multiplexer switch: D-electronics.
(Reproduced from Dirmhrin and Craw, 1971)

taneously until two capsules emerge just above the snow surface at which time the detector receives the xenon flash light. Then they will descend down to the rest position and the snow depth is transmitted to the recorder. A control circuit, a signal generator and other electronics are installed in a capsule at the top of the light receiving pole and they are connected to the in-door instrument of timer and recorder.

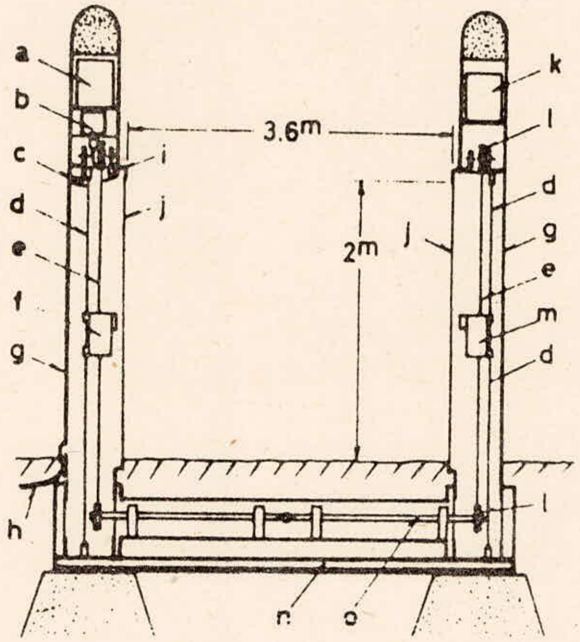


Fig.19 Schematic representation of the instrument
a) Control electronics
b) Driving motor
c) limit switch
d) Scan guide
e) Drive Chain
f) Light receiving capsule
g) Pole
h) Cable
i) limit switch
j) Silt glass
k) light source electronics
l) Ladder wheel
m) Light source capsule
n) Base
o) Connecting shaft

Two ladder wheels are mounted on both sides of a connecting shaft and are linked to another wheels installed at the top of the poles by endless chain. The light source and the detector capsules are attached on the chain and more simultaneously by driving motor. As they move up and down by the same mechanisms, height of two capsules can be kept at strictly the same.

A xenon discharge tube, a focussing lens, and a reflection mirror is installed in the light source capsule. The life of the xenon discharge tube is more than 32, 000 times of discharge, and it is enough for this purpose as it will be replaced by one winter season. Moreover, the bringtness of the xenon flash light is so strong that the broad light beam does not affect the accuracy of the measurement. The detector capsule contains a solar cell of 30 mm diameter and an amplifier. It is possible to detect the very narrow beam of 1 cm or less.

A further improvement in the snow depth-meter was made by Tsuda and Uotsu (1972). It is modified with a redesigned scanning system. The mechanical scanning type was improved with the electrically scanning type which has the array of photo-electric detectors and xenon lamps. On the light source pole and the light receiving pole, 38 xenon lamps and 152 solar cells are mounted at intervals of 8 cm and 2 cm respectively (Fig.20).

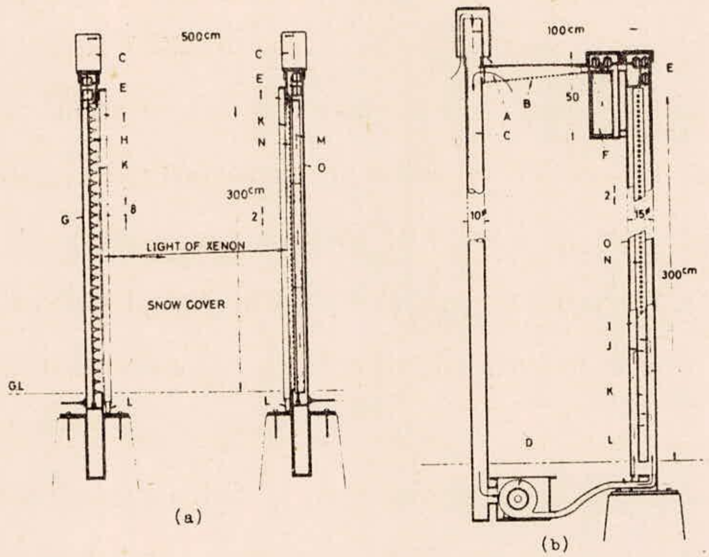


Fig.20 Schematic representation of the modified snow depth meter (Reproduced from Tsuda and Uotsu, 1972)
A) Air intake B) Wire-netting C) Air intake pole D) Blower
E) Connector F) Control electronics G) Light source pole
H) Xenon lamp I) Air duct J) Blast nozzle K) Heater glass
L) Blast pipe M) Amplifier N) Solar cell O) Receiving pole.

2.8.3 Ground Reconnaissance

Snow covered areas are also determined from the ground reconnaissance. However, visual observation from the ground required considerable competence. The coverage can not be as complete as by the aerial survey because of the field of vision and other obstructions such as forests and hills. In addition, travel to vantage points make ground observations expensive and time consuming. During the accumulation season, the use of ground reconnaissance is practical because snow line elevations in mountainous areas are satisfactory index of snow-covered areas. After the onset of the melt season, ground observations are not considered as a means of snow cover determination of a basin.

Miller (1953) compared the simultaneous and independent observations of snow covered area by ground observations and aerial photographic methods. Assuming the aerial photography analysis give the accurate snow cover, the ground estimates of snow cover were found to be too high early in the season and too low in the later season. The estimates of snow cover made from high vantage points, however, were found more reliable than those found from lower, inferior view points.

Ground photographs are generally used as an index of areal snow cover rather than measures of the total snow covered area. Actual snow covered area can be determined by relating these photographic indexes to actual snow cover amounts determined by other means (Potter, 1944). The elevation of the snow line on mountain slopes may be determined by means of photo-theodolite photograph (terrestrial photogrammetry). The theodolite is positioned periodically at predetermined photo stations to photograph the snow line. Terrestrial photogrammetry can be used to advantage in small isolated areas where data are required periodically during the winter and spring seasons. The accuracy is comparable to aerial photogrammetry in such cases.

2.8.4 Aerial Reconnaissance

Aerial reconnaissance is also a most feasible method for obtaining timely and accurate estimates of snow cover. Unlike the results from aerial photography, the aerial reconnaissance makes available the information to the hydrologists as soon as the flight is completed. Its cost is very less than that for obtaining complete coverage by aerial photogrammetric methods. While suitable weather conditions are required for aerial reconaissance, these requirements are considerably less than for aerial photographs.

The methods used have varied depending upon area involved, air craft availability and weather conditions. In general, two procedures have been used successfully. Both consist basically of observing snow covered area and plotting them on a photographic map. In one case, the flight altitude is maintained 4000 to 5000 feet above the highest ridge lines. These heights enable the observer to obtain a fairly broad view of the basin as a whole. The other method is to fly in the canyons approximately at the elevation of snow line. The high level flights require better conditions of visibility. The more comprehensive data of snow covered area is obtained from high level flights. Further, the interpretation of snow covered area from aerial reconnaissance surveys is made by planimetering the areas of snow on the basin map. It is recommended for the aerial reconnaissance that aerial snow cover reconnaissance flights could be scheduled to coincide with ground snow course survey, in so far as possible. Moreover, aerial snow cover surveys should not be made immediately after freshly fallen snow.

The principle disadvantage of this method is that observations of snow under the forest are difficult, regardless of basic methods used, whether from ground or air. However, supplementing aerial reconnaissance with oblique aerial photographs provide continuity between observations and aids in varifying subjective observations.

2.8.5 Aerial Photography

With improvements in both photographic methods and aircraft technology during the past 60 years, aerial photography has developed into a major field of investigation primarily aimed at photographing, interpreting and mapping topography and landscape features.

Aerial photography can be used to provide data on the maximum depth of snow cover in barren and sparsely wooded mountainous basins, as well as the extent of snow cover. For these purposes, aerial photographs of the basin are obtained before the snow season and at about the time of maximum snow accumulation. Snow depth is determined by subtracting photogrammetrically ground surface elevations from similarly deter-mined snow-surface elevations at sample points. Thus, an average depth of snowcover on the basin can be estimated. The accuracy of the determination of the depth of snow cover by this method depends upon the scale of photographs and accuracy of the horizontal and vertical control for the photography. A useful scale for the aerial photography for this purpose is 1:6000 (WMO-1981). For a deep snow cover and favourable photographic conditions, the accuracy may be within ± 10% of the depth of snow cover.

The aerial photography also provides an exact method for determining the area of snowcover. It furnishes a permanent record which can be analysed at any time, and information which can be transferred to basin maps for elevation of true snow cover. Aerial photographs have been used primarily for special studies of snow cover on small basins. Their application to larger snow covered basins for operational use, however, is subject to the following limitations:

(i) The large number of photographs required to cover such basins and time required for photographs processing and evaluation.

(ii) The high cost of operation of aircraft which can operate at higher elevations.

(iii) Difficulty of interpretation of snow cover in forested areas.

Aerial photography is a fairly costly but its principal value is in providing information about quantity and distribution of snow cover that cannot readily be obtained in any other way. The use of aerial photography varies from a supplement to visual observations to a complete and precise delineation of the snow covered area. The regions which are not accessible to ground surveys may be covered by aerial photography.

2.8.6 Satellite Observations of Snow Cover

Among advanced technologies satellite has emerged as a powerful and promising tool for assessment and monitoring of natural resources. Studies of application of satellite imageries of snow cover analysis began in 1960's. In recent years use of satellite imageries to gather information for watershed modelling has assumed great importance to assess snow cover in relatively inaccessible and hazardous regions.

Most of today's mapping of snow covered area is based on image interpretation techniques. Ferguson and Lapezak (1977) made snow cover studies based on NOAA-VHRR data in conjunction with limited ' ground truth' data. LANDSAT imagery supplemented the analysis while image analyser (density slicer) were used to provide grey scale analysis. Drawing of snowline on base maps and latter manual or electronic planimetering of snow covered area provided good results. This method has been considered to be feasible for determining the areal extent of snow cover. Its accuracy is highest over non-forested terrain and lowest over dense coniferous forests where snow cover may only be visible after large cleanings. Hogg and Hanssen (1979) reported that computer enhancement of digital infrared satellite data has worked well to produce snow cover maps and areal estimates are produced without any need to draw a snowline manually. This is how NOAA/NESS produces on a fully operational basis snow covered area data for about 30 watersheds ranging in size from 3700 km^2 to 65000 km^2(Schneider. 1979). An accuracy within ± 5% was claimed for areas greater than 5000 km^2 (Wiesnet. 1974). Lichtenegger et al (1981) determined snow coverage of large areas in high mountains with the aid of a digital terrain model (DTM). It has been shown that this method gives more accurate classification of snow from multispectral LANDSAT data. The DTM makes the independent evaluation of snow possible with respect to elevation, exposure and slope angle.

The use of stereoscopes, zoom-transfer scopes, enlargers, projectors, photographic and density slicers are used world wide to cope with the problems. Interpretation aids such as area contours, base line maps and grid estimation methods have been evaluated (McClain, 1973; WMO, 1973; Barnes and Bowley, 1974). Interactive computers with an operation drawing snow lines through crusor control leading directly to area and percentage figures for the snow covered area, have also been tested (Grid, 1979). The trend in mapping the snow covered area is clearly toward automation, with the human, snow mapping specialists interacting in digital multispectral processing. The evolution of digital technology can also be followed in instrument design and development. Original photography, vidicons, analog image scanners led to today's multispectral digital image devices.

The amount of available data at full resolution is such that in order for large areas and many watersheds to be mapped digital multispectral image processing will soon replace some of the interpretative methods. New techniques have been developed and can be used for either analog or digital image analysis in snow mapping. Overlaying of multi-temporal data, automatic change detection or use of multispectral imagery to enhance certain features are all being tested and evaluated. To-date digital snow mapping tests have been carried out by investigators in the USA (Itten, 1975; Grid, 1979), in Canada (Alfoldi, 1976), in Norway (Odegaard et al, 1979), in New Zealand (Thomas 1979) and in Switzerland (Haefner, 1979). Still a lot of research and development has to take place on this practice in order to cope with tomorrow's information needs.

In some situations, correlations have been found between image brightness and snow depth (McGinnis et al 1975a, Ferguson and Lapezak, 1977), but the interpretation problems are formidable so that a general operational technique employing this type of correlation has not been developed. Because attenuation limits the penetration of visible light into the snowback, it seems likely that snow depth will rely on rediation measurements within other wavelength bands, particularly the microwave band.

World Meteorological Organisation (1976) recommended that for operational hydrological purposes LANDSAT data, NOAA-VHRR imagery and NOAA-SR data be applied to basins with area exceeding 10, 1000 and 10000 km^2 respectively. For hydrological applications it would be desirable that forecasting model be adopted to accept the remote sensing inputs.

Satellite snow cover applications also include regional or hemispheric delineations of snow and ice cover (Wiesnet et al, 1978). The National Oceanic and Atmospheric Administration (NOAA) distributes hemispheric maps of snow cover weekly (NOAA, 1977) and also prepares 10-day composite hemispheric minimum brightness charts detecting snow cover under changeable cloud conditions. These charts are updated daily, recorded on tape and displayed as photographic images. A summary of operational applications of snow cover observation is given by Rango and Peterson (1980).

2.8.7 Limitations in snow mapping by satellite

The mapping of areal extent of snow by a satellite imposed a number of problems:

Cloud Cover: The presence of cloud cover above the snow surface prevents the clear picture of snow. Moreover, it creates confusion whether there is snow or just clouds at a given location. Generally, the pattern of clouds may lead an experienced interpreter to identify them, knowing the expected dendritic appearance of snow in alpine areas. Other data sources like the time lapse capability with geostationary satellites or specific data treatment may help because cloud systems are extremely dynamic features. The clouds in image interpretation also have been recognized because of their shadows on underlying ground.

The Skylab-MSS-S-192 experiment revealed that in the 1.55-1.75 μm wavelength band clouds still appears very bright reflecting, wherever snow shows a very low brightness. This channel would be an operational system to provide an optimum chance to distinguish snow from clouds (Itten, 1975).

Dense Forest: The forest cover may obscure underlying snow and therefore has to be checked very carefully. Forest clearing at different altitudes and aspect angles can offer a possibility in analog interpretation of snow line.

Shadow Effect: In steep mountainous terrain especially with low sun angle in mid winter cause problems in determining snow line. The brightness of snow may under such conditions be reduced to non-snow covered features brightness under normal sun illumination. Hence we can think of different ways to overcome the problem. Instead of using refelected energy, emitted radiation in thermal infrared wavelength bands could contribute to a solution. But also when visible data is combined with terrain formation, ideally in digital terrain model form, shadowing effects can be overcome.

Spatial Resolution: The spatial resolution of a specific system may not be good enough to detect narrow snow covered ridges, snow free valleys on large patchy transition zones. 4 km resolution GOES VISSR data may prove to be very valuable in large watersheds of several thousand km^2 (Schneider, 1979), whereas some small (41 km^2) local watershed that had to be monitored in the Swiss Alps required a spatial resolution of about 100 m (Haefner, 1975).

In an inquiry on mission requirements in a European remote sensing space program found that for European conditions and tasks related to snow mapping a resolution around 200 m would be required (ESA, 1977). As mentioned above, this may not be a useful figure for other regions of the world. The design requirements for snow mapping with a future European remote sensing satellite were defined as follows. It was stated that day-sensing in selected wavelength bands in the visible, near infrared and infrared region of the spectrum and night-sensing in the infrared only was needed at a resolution of approximately 200 m. A repetition rate of nine days was considered necessary to overcome severe cloud cover problems. An optimum local time of 10 a m was proposed for imaging. Additionaly, passive microwave measurements (all weather, day and night) with a resolution of 1 km were deemed necessary for assessment of snow condition parameters (ESA, 1977).

2.9 Measurement of Snow Cover Water Equivalent

The water equivalent of snowcover is the vertical depth of water which would be obtained by melting it. The water equivalent (W) of a snowcover of thickness D is given by

$$W = \sum_{i=1}^{n} d_i \ \rho_i = \bar{\rho} \ D \qquad \ldots(5)$$

where, the snow cover of thickness D has been divided into n homogeneous thickness $d_1, d_2, \ldots d_n$ having densities $\rho_1, \rho_2 \ldots \rho_n$ respectively. The mean density of snow cover $\bar{\rho}$ may be defined by the following relation

$$\bar{\rho} = \frac{1}{D} \sum_{i=1}^{n} \rho_i \ d_i \qquad \ldots(6)$$

A good knowledge of water equivalent of snow pack or snow cover at the end of accumulation season is a vital concern for hydrologists. The main problem is to obtain a reliable figure for the total water equivalent of the snowpack. Great efforts have, therefore, been made to develop reliable methods for estimation of water equivalent of the snow cover. Generally the following methods and procedures are used to obtain water equivalent of the snow cover.

2.9.1 Snow Courses

The common practice in taking measurement is to sample the water equivalent at a number of points along an established line called a 'snow course'. The length of the course and the distance between sampling points vary with site conditions and the uniformity of snow cover. Sample points are located with the objective of avoiding variations in snow depth due to causes such as drifting, interception by trees and presence of boulders or other obstructions. Moreover, the sample points should be located so that they are representative of average basin melt conditions as well as basin snow accumulation. In the hilly terrain a snow course is generally 120 to 270 m in length along which observations are taken at 20-40 m apart. In plain regions, it may be longer with density measurements taken 100-500 m apart and depth measurements made at five, equally spaced locations by measuring its distance from a reference point marked on a map at the snow course. The course may take a shape other than a straight line. The first and last points of the course are generally permanently marked, with intermediate points clearly indicated so that succeeding samples can be taken within a radius of 1 m of each point. Stakes are set high enough not to extend above the deepest snow and offset from the course far enough not to affect the snow cover may be placed as markers opposite each point where snow samples are taken, or at as many points as necessary to minimize possible error in locating the sampling points. Krishnan and Sangewar (1983) used bamboo stakes of two cms diameter and 2-2.5 meter length to study the diurnal depletion characteristics of seasonal snow cover at different altitudes in Rohtang Pass area (H.P.) India.

To establish the water equivalent of the snowpack the samples are taken from the snow surface to the ground by the snow samples. The snow sampler is lowered vertically into the snowpack with steady thrust downward. The basic snow sampling equipment consists of a graduated tube with a cutter fixed on its lower end to permit easy penetration of the snow and a spring balance to weigh the tube and its content. Most of the tubes are made of aluminium, others are fiber glass or plastic. In every snow sampler's design the inside diameter of the tube is kept slightly larger than the inside diameter of the cutter to allow the snow cover to move freely up in the tube. The waxing and polishing both the inside and outside of the tube help to minimize friction between snow cover and the inner-wall of the tube and to prevent the tube from sticking in the snow. The recent tests have pointed out that a baked silicone coating on the tubes is more effective and durable than waxing for these purposes. Various types of snow samples and snow tubes are shown in Figs.21 and 22. The snow sampling in the field by a snow sampler has been shown in Fig.23.

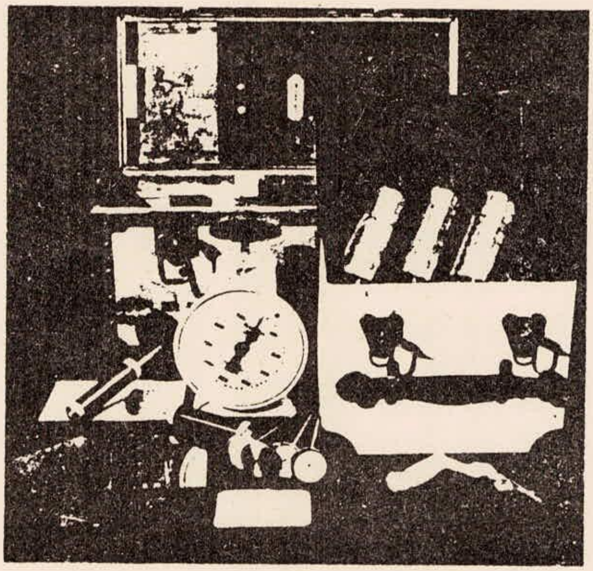
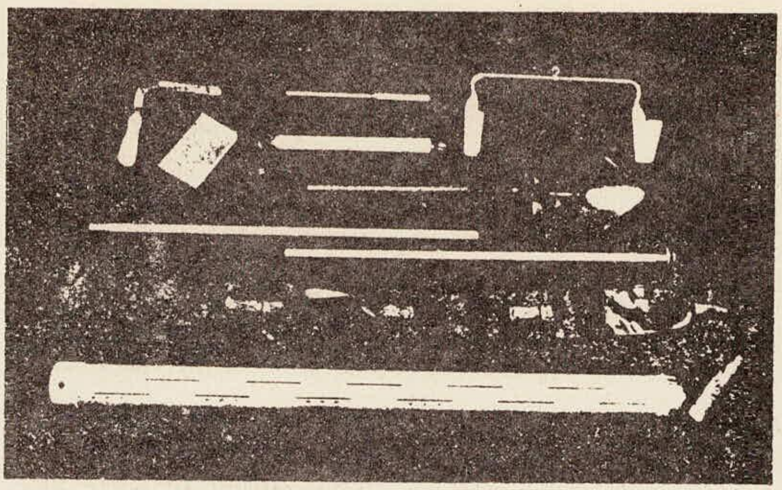
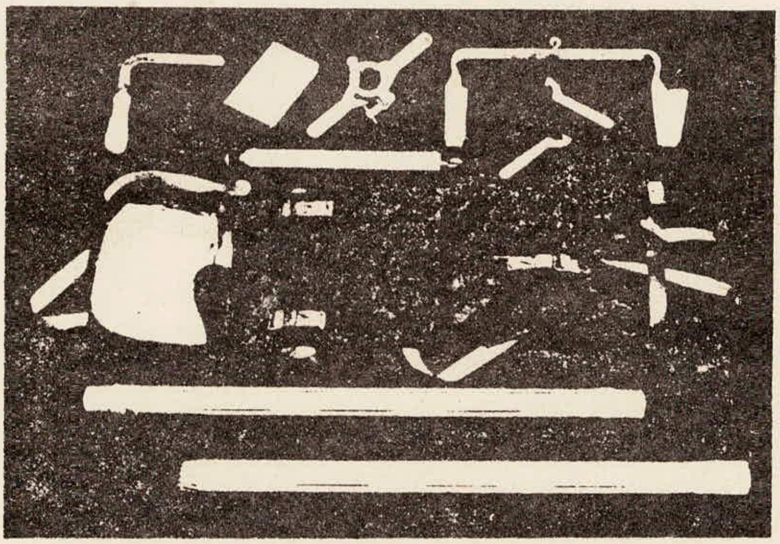


Fig.21 CRREL snow tubes

Washicheck et al (1963) has summarized the developments of the standard gravimetric measurements using snow samplers to obtain snow sample cores. Research has shown that the standard snow-tube measurements, such as those obtained by the Federal or Mount Rose types, tend to overestimates the water



(a) Canadian MSC snow sampler



(b) Standard Federal snow sampler

Fg.22 Snow samplers used in North America.
(Reproduced from Gray and Male 1981)

equivalent of the snow cover about 7 to 12%. depending upon the depth and density. Improved accuracy for light snow cover, less than 15 cm of water equivalent may be obtained by the use of samplers with larger diameter such as the Adirondack snow tube (Work et al. 1975). However, such larger diameter tubes are not satisfactory for use at depths greater than about 1 meter. The larger diameter snow samplers used for shallow snow cover water equivalent are a single tube. while smaller diameter samplers for deeper snow packs are in sections for easier portability. The properties of various types of snow samplers has been listed in Table 8.

Fig.23 Snow sampling in the field by the use of snow samplers

Tests suggest that a sharp federal sampler is suitable for use in all types and depths of snow cover. Similarly. the Adirondack sampler provides consistent. accurate samples in snow. where ice layers do not restrict its ability to obtain a core. The Canadian MSC sampler has found satisfactory use in the shallow snow covers. However. the testing of modified versions of the standard samplers and cutter is continuing in order to improve their performance under different snow cover conditions (Fares et al. 1980).

2.9.2 The Pressure Snow Pillows

Increased costs for obtaining samples by having personnel travel to

TABLE 8 - Snow Sampler Properties

	Standard[a] Federal	Federal[b]	Bowman[c] L-S	McCall[d]	Canadian[e] MSC	Adirondack[f]
Material	Aluminum	Aluminum	Plastic or Aluminum	Heavy Gauge Aluminum	Aluminum	Glass Fiber
Length of Tube[g] (cm)	76.2	76.2	76.2	76.2	109.2	153.7
Theoretical ID of cutter (cm)	3.772	3.772	3.772	3.772	7.051	6.744
Number of teeth	16	8	16	16	16	None[h]
Depth of snow that can be sampled (m)	> 5	> 5	> 3.5	> 5	1.0	1.5
Retains snow cores readily	Yes	Yes	Yes	Yes	No	No

[a] Standard sampler used in the Western United States and Canada.
[b] Identical to "Standard Federal" but has an 8-tooth cutter.
[c] Cutter has alternate cutter and raker teeth and may be mounted on plastic or standard aluminum tubing. It is more an experimental rather than operational sampler.
[d] Used in dense snow or ice. It is a heavy gauge aluminum tube with 5-cm cutter with straight flukes. It may be driven into the pack with a small slide drop hammer producing an ice pick effect.
[e] Atmospheric Environment Service large diameter sampler used in shallow snowcover.
[f] Large diameter fiberglass sampler commonly used in Eastern United States.
[g] Most snow samplers in North America use inches and tenths as their basic units of measurement. Values in this table are corresponding metric equivalents.
[h] Stainless steel circular cutter edge or small teeth.

the snow areas and the need for more rapid acquisition of the information have led to the development of sensors that can be read remotely and automatically. One of these sensors is the pressure snow pillow (Fig.24). It consists of a pillow made of neoprene, a rubber like compound. It is filled with anti-freeze liquid and a pipe connects the pillow to a stilling well. Some of the liquid will be pressed in to the stilling well by the weight of the falling snow and thus the liquid level in the well is directly related to the water equivalent of the snow pack on the pillow. Variation in load on the pillow may be recorded by the means of an automatic water level recorder. On site and/or telemetry data acquisition systems can be installed to provide continuous measurements of the water equilvaent through the use of a stand pipe and float actuated charts or digital recorders. Alternatively, the pressure changes in the pillow can be monitored by a transducer, whose electrical output can be interfaced into a telemetry system.

The snow pillow assumes that snow acts as a perfect fluid and unusual conditions can affect the accuracy of the measurements. Beaumont (1965) described the use of snow pillow in the United States whereas Tollon (1970) in the Norway. The pressure pillow has proven to be a fair indicator of actual water equivalent of snow cover in many heavier snow areas, especially during the primary snow accumulation period. Some times pressure plates are also used rather than original butyl rubber pillow. The size of the pressure plate or snow pillow necessary for best accuracy depends on the amount of snow cover normally expected. The greater depth of snow requires larger size of pillow cover. In shallow snow cover, diurnal temperature changes may cause expansion or contraction of the antifreeze solution in the pillow giving spurious indications of snowfall or snowmelt. In deep mountain packs, diurnal temperature fluctuations are unimportant except at the beginning and end of the snow season.

The pressure pillows come in various shapes, sizes and materials. First experiments were made with six feet and twelve feet diameter pillows made of plastic, but the occurrence of leaks in pillows led to the use of tougher material, namely a 0.064 inch nylon reinforced butyl rubber. Now-a-days the pillows are fabricated from butyl rubber, neoprene rubber, sheet metal or stainless steel, and are filled with an anti-freeze mixture of methyl alcohol and water or methanolglycol-water solution having a specific gravity of 1.0 (Mayo, 1972). Octagonal or circular pillows are most common, however shape does not affect the measurement accuracy. Barton (1974) recommended the following minimum pillows sizes (m^2) for specific snow cover water equivalent (mm):

3.7 m^2 size for water equivalent less than 750mm

5.6 m^2 size for water equivalent less than 750-1270 mm

7.4 m^2 size for water equivalent less than 1270-1900 mm

11.2 m^2 size for water equivalent greater than 1900 mm

Beaumont (1965) reported that a 3.66 m diameter pillow generally is large enough for most snow cover depths, however a small pillow used in a deep snow will give a pressure reading indicating a higher snow cover water equivalent that of the snow on the pillow. In such cases smaller pillows take longer time to respond the added weight of a heavy snowfall on a deep pack than larger pillows, this delay can produce an erroneous depth time distribution of storm. Tarble (1968) reported delayed responses of 5 hours (3.66 m diameter pillow) and 10 days (1.5 m diameter pillow) under certain conditions. Accessibility of a site also influences the installation. Large pillows are bulky and required a large volume of antifreeze that is heavy and difficult to transport. As an alternative, small easily transported metallic pillows (1.22 m by 1.52 m) which may be combined to obtain a large surface area are now in common use (Waschichek, 1973).

Results from a snow pressure pillow are regarded as being more representative than single samples taken by the snow samplers, provided the pillow is properly installed i.e. it must not be subject to winds, traffic or any other disturbing factors. The results are most reliable when snow cover does not contain ice layers, which can cause bridging above the pillows.

2.9.3 Natural Gamma Radiation

2.9.3.1 Aerial Survey

The use of natural gamma radiation from the earth as a means of measuring the water equivalent of the snow cover was initially developed in Soviet Union (Kogan et al, 1915; Dmetriev et al, 1971; Grasty and Holman, 1972). Dahl (1970) used same approach in Norway and such techniques have also been used in United States (Peck et al, 1971; Peck and Bissell, 1971).

This method is based on attenuation by snow of gamma radiation emanating from natural radioactive elements in the top layer of the soil and rocks.

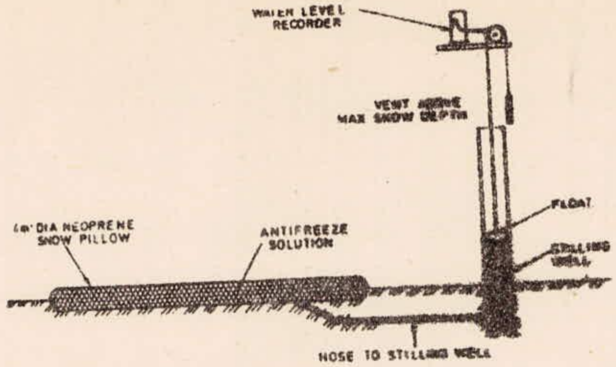


Fig.24(a) Snow pressure pillow

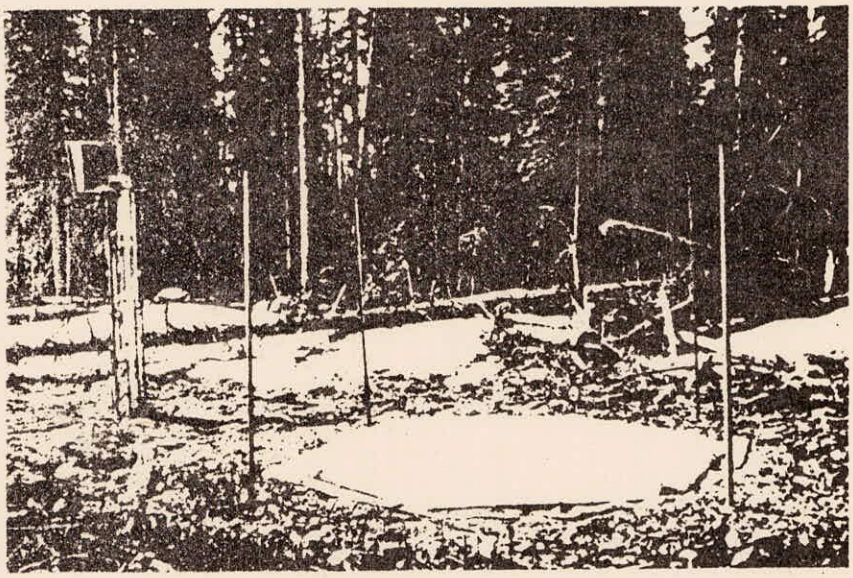


Fig.24(b) Sketch showing the principle of gamma survey of snow cover

The greater water equivalent of the snow, the more radiation is attenuated. The ratio of gamma radiation intensity measured above the snow cover to that measured over the same course before snowfall provides an estimate of the water equivalent. In the aerial surveys, a gamma ray sensor and a recording device are installed in a low flying aircraft Fig.25. A continuous record of the variation in natural gamma radiation along a given flight line are obtained by making observations time to time. It is extremely necessary to fly along the identical lines because a relatively small deviation from it may introduce errors due to existence of other rocks and different radiation properties than those measured previously. Consequently, the flight line must be selected very carefully so that the pilot can follow them year to year.

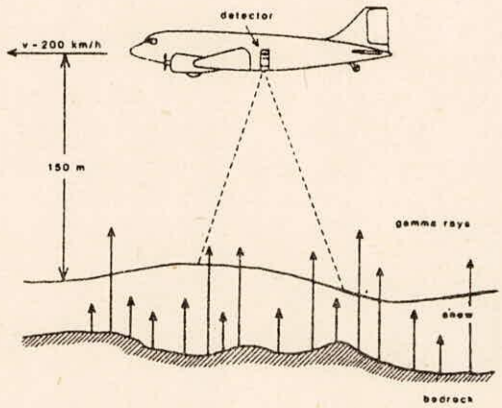


Fig.25 Sketch showing the principle of gamma survey of snow cover

The estimation of water equivalent of snow cover is possible because all water (in any form) attenuates the gamma rays so that an identical flight during the winter will produce a different record of gamma radiation than in the summer. Measurement consists of total count for a large energy level and for specific energy levels (spectral data). The spectral information permits correction for spurious radiation induced by cosmic rays and radioactive of the atmosphere. Similar results may be obtained by using a special protective shield for cosmic rays and two detectors of different sensitivity. The water content of the snow is determined from the following relationships.

$$R_w = R_s e^{-\alpha W_n}$$

whence

$$W_n = \frac{\ln Rs/Rw}{\alpha} \qquad ..(8)$$

Here

Rs = intensity of soil ground gamma radiation at height Z, with no snow cover

W_n = water equivalent of snow

R_w = intensity of gamma radiation with water equivalent W_n

α = Constant of sensitivity of the instrument.

Surveys may be made at altitudes upto 300 m, but are most accurate at the lowest altitude possible for terrain. The gamma radiation survey method is most reliable for level terrain but can also be used for hilly areas with elevation difference upto 400 m (WMO, 1981). The accuracy of the water equivalent depends on the limitations of the radiation measuring equipment, soil moisture variation etc and ranges between ± 10%. The aerial survey can be used to measure water equivalent of 10 to 100 mm.

A great advantage of the natural radiation survey method is that it yields average water equivalent over the path along the line of flight. The effective width of the path is approximately two to three times of altitude. Moreover, the attenuation rate of the gamma rays in snow is determined solely by the water mass independent of its state. The advantage of this method over the use of artificial radiation sources is the lack of a radiation hazard. However, the moisture of air, navigation errors and water in soil and loose deposits cause errors in the observations. In order to obtain the water equivalent of snow cover an area upto 3000 km^2, with an error not exceeding 10%, the following length of courses (L) and distances between courses (s) are recommended (WMO, 1981).

Recommended lengths of flight courses (L) and distance between courses(S)

Natural regions	S(km)	L(km)
Forest-Steppe	40-50	25-30
Steppe	40-50	15-20
Forest	60-80	30-35
Tundra	80-100	35-40

2.9.3.2 Ground Survey

A hand carried detector provides a mean for measurement of averaged water equivalent for a band width of approximately 8 meters for the length of the course. The equipment includes a portable gamma-ray spectrometer which utilizes a small scintillation crystal to measure the rays in a wide spectrum. With this system, pre-snow or no-snow measurements of gamma level are required at the point of along the traverse being studied.

The mean intensity of gamma radiation (R_i) on the course before (R_o) and after (R_t) the appearance of the snow cover is calculated by means of the formula:

$$R_i = \frac{N-32}{t} - R_r \qquad \ldots(9)$$

where,

N is number of pulses recorded by the counter of the instrument

32 is a coefficient of division of the recalculating circuit.

R_r is the residual background of the instrument, determined from atmospheric pressure.

The table of graduations of the instruments giving the value of the coefficient of attentuation of gamma radiation R_t/R_o, approximate mean values of the water equivalent , $\breve{w}_n$(mm) of the snow cover are found of the course. The ture value $\bar{w}_n$ is obtained after applying a correction allowing for variation in the cosmic background and terrestrial background :

$$\bar{w} = K\,\breve{w}_n$$

$$K = R_1/R_2$$

where,

R_1 is the background radiation, measured over a period of 10 minutes before starting the snow measurement.

R_2 is the background radiation. before the appearance of snow cover, the time of measurement also being 10 minutes.

Water equivalent from 10 to 300 mm may be measured by this technique. The accuracy of the measurements ranges from ± 2mm to ± 6 mm depending on changes in soil moisture, distribution of the snow, as well as the stability of the instrument system.

2.9.4 Radioisotope Snow gauges

Nuclear techniques are widely used in this field of hydrology. Many gauges have been designed in the past few years based on the principle of attenuation of radiation from the radioactive gamma sources by the mass of snow cover. One type of installation (vertical) is used to measure water equivalent above the radioactive gamma radiation source. A second installation (Horizontal) measures water equivalent between two vertical tubes at selected distances above the ground.

2.9.4.1 Vertical Radioisotope Snow gauges

The earliest gauges which measured total water equivalent of the snowpack consisted of a radiation source (^{60}CO) placed on the ground with a detector (Geiger-Miller or Scintillation counter) over head. The high energy source of gamma radiation Cobalt -60 is used for this purpose because of its high gamma energy and long life(5.25 years). The detector is suspended at a height greater than the maximum expected snow depth. As snow is accumulated, the count rate is decreased in proportion to the water equivalent of the snowpack (Gerdel et al. 1950: Strenzat and Sapozhnikov, 1959). The source of radiation may also be placed in the soil at certain depth (50-60 cm) so that gamma rays pass not only through the snow cover but also through a layer of soil. Thus it is possible to obtain data during the melting of snow as to the quantity of water permeating into soil or flowing off the surface. Some researchers reversed the position of the source and counter also (Higoshi and Itogoki, 1956). This arrangement reduces temperature variations of the detector and provides a constant background count.

Radio-isotope snow gauges are a non-destructive method of sampling and are adoptable to onsite and/or telemetry systems. Most practically, those employing an artificial source of radiation are used at a fixed location to yield measurements only for that site. Portable gauges have also been developed and tested in fields (Young, 1976). This method can be used for depth of snow-pack equivalent upto about 100 cm with a standard error of 1.8 cm using radiation source of permissible strength. Increasing the strength of radiation source permits read out from an aircraft (Jordon, 1970) but required considerable protection for environmental safety. More recently, a system using naturally occuring uranium as a ring source around a single pole detector has been successfully used to measure packs upto 500 mm water equivalent or 150 cm depth (Morrison. 1976). Rao et al (1983) also made some studies in gamma attenuation for application in snow gauges. The proposal is based on the result obtained from preliminary feasibility and simulation study carried out in the laboratory to estimate the water equivalent thickness of snow.

This system provides continuous information on increments of snowpack accumulation from storm to storm throughout the accumulation period and also provide a means of evaluating increments of melt during the ablation period from an undisturbed snow sample point at a remote site. However, installation of isotope snow-gauges requires relatively expensive, and complex instrumentation.

2.9.4.2 Horizontal Radioisotope Snowgauges

The profiling isotope snowgauges which measure the vertical profile of the water equivalent and density of snowpack between two vertical poles at selected space have been developed in France. United States and Canada (Smith and William, 1964; Gosselin, 1971; Warnick and Penton, 1971; Smith et al, 1972). A horizontal isotope snowgauge consists of two parallel vertical access tubes, spaced about 66 cm apart, which extend from the cement base in the ground to a height above the maximum expected depth of snow. One tube contains gamma radiation source (30 m c_i of $^{137}C_s$) and the other a detector (Geiger-Muller tube or sodiaum Iodide NAI (TI) scintillation crystals). The source and detector are set up at a equal depth within the snow cover and coupled together so that they rise and lower exactly in the same level.

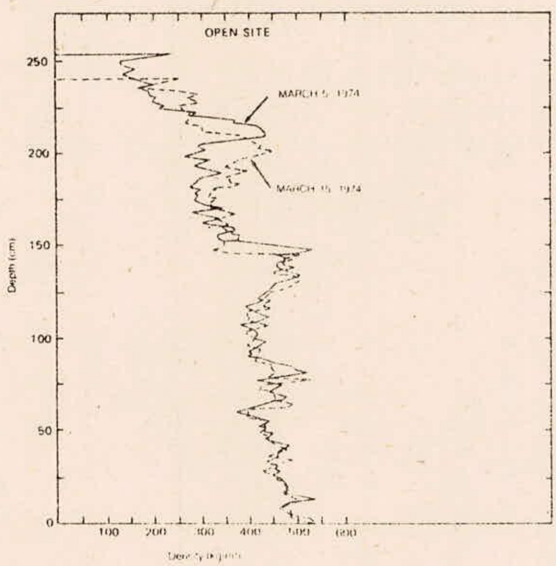


Fig.26 Profiles obtained from nonforested site, CSSL with profiling snow gauge (U.S.Dept. of Agr.Forest Service, 1974)

The measurement of the attenuation at each selected distance above the ground is a measure of the water equivalent at that height. Successive measurements are obtained at selected vertical intervals to obtain a profile of the water equivalent. Very accurate vertical density profiles are obtained by taking measurements at about 2 cm increment of depth. Thin ice lenses or rapid density changes are readily detected by this system (Fig.26). Data on density profile and on the rate and amount also of the new snow accumulation are also important in Avalanche Studies (Armstrong, 1976).

2.10 Comparison of ground based snow cover water equivalent measurement techniques

Accuracy in the measurements for determining point or areal water equivalent is always a question in such studies. The method selected depends on the purpose of the study and the manner in which the data is used. Snow surveys data are the ultimate base of comparison for other snow cover system measurements.

Warnick and Penton (1971) made a comparison of the snow cover water equivalent from isotope snowgauge, pressure pillow snow gauge (4 meter diameter) and snow tube. It was found that isotope gauges provided reliable, inspite of the complex electronic circuitry and equipment involved, and their accuracy is at least as good as that of the snow tube and in many cases much better. Waldron (1967) indicated that a G-M detection system for the isotope can be almost as accurate as the scintillation system and has the advantage of simplicity in construction.

Morrison (1976) found appreciable differences between the snow cover water equivalent measurements made with a pillow, isotope gauge and snow tube (Fig.27). It was reported that water content of the snow cover measured by the snow pillow was consistently less than a corresponding values obtained by the other methods was attributed to bridging.

Figure 28 compares three years records obtained from a 3.66 m diameter snow pillow and a standard 10 points snow course located at a sheltered mountain site in British Columbia (Gray and Male, 1981). It is apparent from these results that there is a reasonable agreement between the two methods.

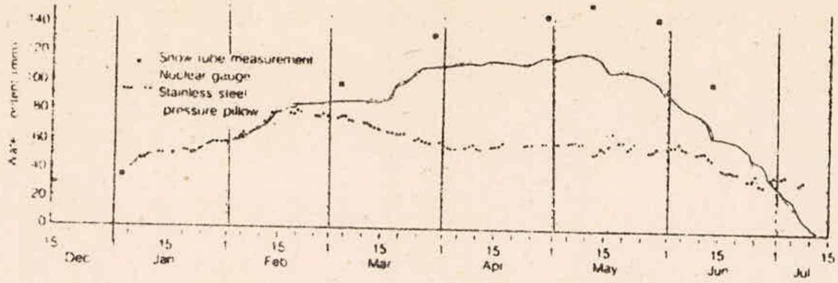


Fig.27 Comparison of snow pillow, nuclear gauge and snow tube measurement at Boise River Drainage Basin, Idaho (Morrison, 1976).

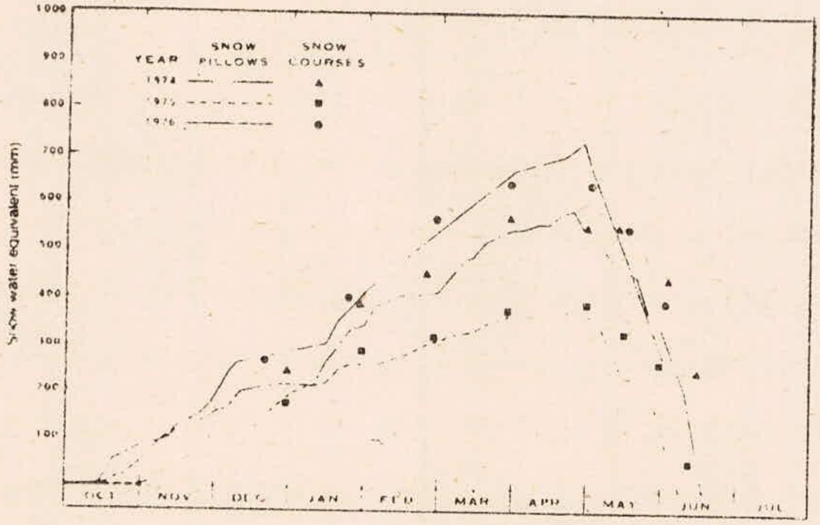


Fig.28 Comparison of snow pillow and snow course measurements near McBride B.C. (Reproduced from Gray & Male , 1981.)

A district advantage of the pressure pillow is that it provides continuous records of the snow water equivalent.

2.11 Measurement of Snowfall and Snow Cover in India:

In India snow surveys were conducted for the first time in mid forties. In 1947 two snow survey parties were made under the overall guidance of Dr J.E.Church, a meteorologist from Agricultural Experiment Station, Reno, Nevada, USA and the then President of the International Commission on Snow and Glaciers. Dr.Church was the man to initiate snow surveys and stream flow forecasting in Himalyas. During that period the snow surveys were conducted in Tamur and Tista catchments. Darjeeling was fixed as a base camp for both parties.

2.11.1 Snow Pole

In the areas where the precipitation is only in the form of snow, the following method of snowfall is adopted. A square plate-form 2x2m and 75 mm thick is made of cement concrete 1:3:6 at ground level in a place where drifting due to snow is least. Generally a scale is fixed permanently at the centre of the platform. A 50 mm square wooden scale projecting 3 m above the level of platform is grouted 1 m below it (IS: 4986). The pole is graduated in metric systems and painted on four sides of the pole. Generally an another scale in the form of a wooden stick of 25 mm square having metric graduations is also provided to the station. While taking the observations, first central scale is read for the depth up to which it is submerged in snow and with the help of the other scale the depth of snowfall at four other corners of the platformis read. The mean of the five reading is taken as the amount of snowfall. At the end of each observation, the snow of the platform is cleared so that the next snowfall measurement is not vitiated by the snow accumulation which has already been measured. The mean depth of snowfall in millimeters divided by 10 approximately gives the water equivalent of snow in millimeters.

2.11.2 Snow Gauges

In case of snow and frozen rainwater standard gauges are used. The amount of snow collected in the cylindrical gauge is melted by adding through the funnel an adequate quantity of warm water. accurately measured with measuring glass. The total water content in the receiver is measured which gives the total of snowmelt water and added warm water. The water equivalent of snow is determined by subtracting the added warm water from the amount of total measured water content. When the snowfall is heavy. the reading of the snowgauges might become unreliable in the event of the gauge being entirely under snow or in the event of the snow being blown away by wind. Under such conditions all the snow accumulated over the collector is pressed into the funnel and melted. This melted water represents the water equivalent of the snow. The snow gauge in use in India consists of a simple cylindrical collector having a diameter of 230 mm. The gauge is normally exposed at a height of about 2 m above the ground. mounted on a metal stand with a Napier Shield. This gauge is now being replaced by a new snowgague with a 500 cm^2 collector and an Alter Shield. IMD is one of the organisation to use such gauges in the Himalyan region.

The snow and Avalanche study Establishment (SASE). Manali H.P. started snow observation on large scales in the Himalyan region since 1969 onward. The daily observations are transmitted to the SASE by wireless system from the remote area observatories. Recently in 1984. Central Water Commission has also initiated activities on snow observation in Yamuna catchment. The efforts are in progress to measure snowfall water equivalent by tipping bucket precipitation gauge with heating system.

2.11.3 Snow Cover

A number of organisations in India such as NRSA, ISRO, GSI, IMD, NIH, SASE and University of Roorkee etc. have experience in mapping of snow covered areas from satellite imagery and using the same for snowmelt runoff studies. Dhanju (1982-83) revealed that remote sensing could provide a reasonable estimate of snow covered area which would form the basis for estimating meltwater for long term and short term periods. Jeyaram and Bagchi (1982) estimated snow line altitude and snow cover using LANDSAT imagery for Tos basin in Himachal Pradesh. NRSA has taken snow melt runoff forecasting studies using NOAA satellite data (Ramamoorthi, 1983). In order to determine depth, density and water equivalent of snow cover at a place during accumulation and ablation period snow surveys are conducted by SASE and CWC. The federal snow samplers are used by CWC for snow sampling. Stainless steel snow pillows are also being used for snow cover water equivalent by CWC.

3.0 REMARKS

The shielded Nipher gauge has shown a superior catch efficiency compared to other snow gauges. However, this gauge needs to be attended daily by the observers. Alter shielded Fischer and Porter gauge has a relatively poor catch efficiency, but it is more suited for use in research and experimental basins or at long term remote observing stations. At transient temperature around $0^{o}C$ in the vibrating wire strain gauge some of the snow fasten to the inner side of the inlet tube - falls into bucket after a while by solar radiation heating. This effect is observed as a time delay of snowfall in some cases. This system is also well suited for remote areas and can be placed more than one kilometer away from the reading equipment without any loss of information. Comparative study of snow gauge is yet to be performed in India.

Various factors such as wind speed, air temperature and gauge confirguration affect the catch of the gauges. Shielding of the gauges has exhibited an appreciable increase in the snow catch in comparison to unshielded gauges. For example, at wind speed of 5 m s^{-1}, the Alter shielded Fischer and Porter gauge caught 40% of the ground true whereas unshielded counterpart caught only 21%. The shielded gauges are not well suited yet to give reasonable snow catch efficiency at the sites exposed to strong winds. There is not a universal correction factor applicable to all gauges for storm conditions.

Tests have suggested that a sharp Federal Sampler is suitable for use in all types and depths of snow cover. However, this slightly overestimates the water equivalent of the snow cover. The over-estimation by the Federal Sampler originates from the design of the cutter point which tends to force snow to move into tube than the inside diameter of the cutter. The Adirondock sampler also provides consistent, accurate samples in snow where ice layer does not restrict its ability to contain a core. In addition to elevation, factors such as slope and exposure have an effect upon distribution of snow on a basin. Therefore, a snow course at a given elevation does not necessarily represent the water equivalent at that elevation throughout the basin. An adequate sampling of range of elevation could be made in order that varying slopes of snow wedge may be evaluated.

Pressure pillows are widely used to obtain continuous record of the snow water equivalent. Such pillows have also been used in measuring water equivalent of shallow snow cover where bridging did not occur. The rough estimates of the daily snow melt losses from the snow cover may also be obtained by snow pillows. However, in shallow snow cover, diurnal temperature changes cause expansion or contraction of the fluid in the pillow giving spurious indication of snowfall or snowmelt. The accuracy of larger pillows appears to be good and units are reasonable in cost and easy to service.

To obtain absolute estimates of the snow water equivalent by terrestrial survey of natural gamma radiation, it is necessary to correct the readings for soil moisture changes in the upper 10 to 20 cm of the soil for variation in background radiation resulting from cosmic rays, instrument shift, and washout of radon gas in the precipitation with subsequent build up in the soil or snow. In the aerial survey method of natural gamma radiation correction due to mass of the air between aircraft and ground should be made. The mass of the air may be obtained from measurements of the atmospheric temperature and pressure at flight levels and at ground to compute correction factor. Radon gas present in the atmosphere also emits gamma radiation which particularly affects computation involving the total count data. The radioisotope snow gauges scintillation system has many component parts that require much care in operation and such units are expensive. However, isotope snow gauges provide reliable information about snow water equivalent. The necessity for periodic calibration of such gauges in the field has also been one of the limitation in the snow bound areas.

The determination of snow covered area from ground photography is extremely difficult especially for rugged mountainous areas. The procedure is subject to considerable personal judgement and requires experience in taking photography. The observation of snow under forest is a formidable problem through ground photography. Increasing use of aircraft for snow cover observations, however, made mountainous areas readily accessible for both visual and photographic observations. In such surveys near-ideal weather conditions are required during periods when snow cover observations are made. A large number of photographs are needed to assess the snow cover of large basins. Moreover, for routine observations a considerable time is required for processing before picture are ready for analysis.

An accurate estimation of snow cover extent and its time spatial distribution is obtained by remote sensing methods using satellite imagery and computer. A repetition satellite imagery monitor snow cover qualitatively and quantitatively. In India also satellite imagery and satellite data are being applied successfully for mapping and monitoring of snow cover. However, satellite imagery could not provide any information either about the snow depth or about the water equivalent of the snow. Some efforts have been made to correlate snow covered area and subsequent melt water runoff. Forthcoming new satellite systems with improved spectral band selection, better resolution, improved repetition rates, rapid access of data will contribute to a better understanding of how and when things happen. This will greatly enhance the accuracy in snow monitoring and mapping.

In India the snow measurements are not adequately carried out which make it difficult to estimate the snow cover and its water equivalent. Even snow surveys are being made in a very limited way. There are few snow gauges installed in mountainous regions and those also are without shielding, which do not represent the actual catch of snow. To obtain reliable observation Nipher shielded gauges may be used in India. The feasibility of recording snow gauges is still to be tested. The number of snow gauges including establishment of snow courses need to be augmented. Other methods using sequential LANDSAT imageries in conjunction with temperature data are in progress for snow accumulation characteristics on Himalayan slopes. Besides the snow cover assessment, the need of estimation of snow pack depth, density etc. also require further application of satellite information obtained at particular intervals.

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