PD CEN/TR 16588:2014

BSI Standards Publication

Manual measurement of snow water equivalent

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National foreword

This Published Document is the UK implementation of CEN/TR 16588:2014.

The UK participation in its preparation was entrusted to Technical Committee CPI/113, Hydrometry.

A list of organizations represented on this committee can be obtained on request to its secretary.

Published by BSI Standards Limited 2014

ISBN 978 0 580 77502 4
ICS 07.060

This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 March 2014.

Amendments/corrigenda issued since publication

Date	Text affected

TECHNICAL REPORT
RAPPORT TECHNIQUE
TECHNISCHER BERICHT

CEN/TR 16588

March 2014

ICS 07.060

English Version

Manual measurement of snow water equivalent

Mesure manuelle de l'équivalent en eau de la neige

Manuelle Messung des Schneewasseräquivalents

This Technical Report was approved by CEN on 3 September 2013. It has been drawn up by the Technical Committee CEN/TC 318.

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EUROPÄISCHES KOMITEE FÜR NORMUNG

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Ref. No. CEN/TR 16588:2014 E

Contents

Foreword

This document (CEN/TR 16588:2014) has been prepared by Technical Committee CEN/TC 318 “Hydrometry”, the secretariat of which is held by BSI.

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Introduction

Snow water equivalent (SWE) measurements

Snow water equivalent (SWE), also called “water equivalent of snow”, is the depth of water that would be obtained by melting the snowpack in a given area, and is normally expressed in millimetres. In other words, SWE corresponds to the mass of snow over a given area.

Measurements of SWE in snowpack, and new snow, improve the estimation of winter precipitation, especially in areas with a sparse network of meteorological stations. The measurements are mainly made for the purpose of estimating the spatial distribution of the total water content in catchment areas, as knowledge of the SWE in river basins is fundamental for estimating the expected snowmelt runoff.

Information about snow accumulation and daily melt rate is essential in flood forecasting during the snowmelt season. SWE is also used in avalanche theory and forecasting, as well as for risk assessment of heavy snow loads. Furthermore, the data is important in glaciological mass balance studies and climate monitoring. The melt from polar ice sheets is a major factor in sea level rise.

Methods and instruments, which have been developed for determination of SWE, are listed in Annex A.

Manual SWE measurements

The first station networks with manual SWE measurements were established in the early 20th century at meteorological institutes in North America and Europe. Today the measurements are made routinely at federal and national meteorological and hydrological institutes, within the hydropower industry, and by universities, in cold climate countries all over the world. Annex B shows a list of manual SWE measuring bodies in Europe.

Automized methods have been developed to be used in remote areas, as well as to enable continuous recording, but manual measurements are still more common, as they can provide high quality data for a relatively low capital cost. The importance of manual measurements is also reflected in their use as reference to other SWE measuring methods.

1 Scope

This Technical Report defines the requirements for manual measurements of SWE over land, see ice and glaciers, under natural environmental conditions, and shows methods for calculating the spatial distribution of the data. It includes measurements with snow tubes, core drills and density cutters.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

Note 1 to entry Primarily ‘The International Classification for Seasonal Snow on the Ground’ (UNESCO), ‘Cryospheric Glossary’ (NSIDC) and ‘Glossary of Meteorology’ (AMS) has been used as reference.

2.1
ablation
removal of material from the surface of an object by vaporization, chipping, or other erosive processes. In this case the opposite of *snow accumulation*

2.2
blowing snow
an ensemble of snow particles raised by the wind to moderate or great heights above the ground; the horizontal visibility at eye level is generally very poor

Note 1 to entry See also *drifting snow*.

2.3
condensation
the change of the physical state of matter from gaseous phase into liquid phase (opposite of *evaporation*)

2.4
deposition
(1) a process by which water vapour is deposited as ice without first forming liquid water (opposite of *sublimation*)

(2) the process by which snow is deposited on the ground either with or without wind action

Note 1 to entry As a result, stationary snow deposits such as snow dunes, *snowdrifts*, or the *snow cover* itself may form.

2.5
drifting snow
snow raised from the *snow surface* by the wind to a height of less than 2 metres; it does not restrict horizontal visibility at 2 metres or more above the surface

Note 1 to entry See also *blowing snow*.

2.6
evaporation
vaporization of a liquid that only occurs on the surface of a liquid, at temperatures below the boiling point (opposite of *condensation*)

2.7
firn
well-bonded and compacted snow that has survived the summer season, but has not been transformed to *glacier* ice

Note 1 to entry Typical *densities* are 400 - 830 kg·m^{-3}. Thus firn is the intermediate stage between snow and glacial ice where the pore space is at least partially interconnected. Firn usually results from both melt-freeze cycles and compaction by overload, or from compaction alone, as in inland Antarctic snow.

2.8
glacier
a mass of land ice formed by the further *recrystallization* of *firn*, normally flowing continuously from higher to lower elevations

2.9
new snow
recently fallen snow in which the original form of the ice crystals can be recognized

Note 1 to entry This is usually the snow which has accumulated on a snow board during the standard observing period of 24 hours.

2.10
old snow
deposited snow whose transformation into *firn* is so far advanced that the original form of the ice crystals can no longer be recognized

2.11
recrystallize
to crystallize again, i.e., to form into new crystals

2.12
redistribution
distribution of previously *deposited snow* that was *eroded* and transported by the wind

Note 1 to entry Redistribution features such as *snowdrifts* are usually formed from densely packed and friable snow.

2.13
perennial snow
snow persisting for an indefinite time longer than one year

Note 1 to entry See also *seasonal snow*.

2.14
seasonal snow
snow that accumulates during one season and does not last for more than one year

Note 1 to entry See also perennial snow.

2.15
snow accumulation
all processes that add mass to the *snow cover*, i.e. typically solid and liquid precipitation, ice *deposition* from atmospheric water vapour, and snow deposited by wind, *avalanches*, etc. (opposite of *ablation*)

2.16
snow avalanche
mass of snow which becomes detached and slides swiftly down a slope

Note 1 to entry Large snow avalanches may contain rocks, soil, vegetation, and/or ice.

2.17
snow board
in this case a specially constructed board used to identify the surface of snow that has been recently covered by *snowfall*

2.18
snow core
a *sample of snow*, either just the freshly fallen snow or the combined old and new snow on the ground, obtained by pushing, or drilling, a cylinder down through the *snow layer* and extracting it

2.19
snow course
an established line, or transect, of measurements of SWE across a snow covered area in a representative terrain, where appreciable amounts of snow accumulates

2.20
snow cover
in general, the *accumulation of snow* on the ground surface, and in particular, the areal extent of snow-covered ground; term to be preferably used in conjunction with the climatologic relevance of snow on the ground

Note 1 to entry See also *snowpack.*

2.21
snow creep
a continuous, slow downhill movement of a snow layer

2.22
snow density
the mass per unit volume of snow

Note 1 to entry Sometimes total and dry snow densities are measured separately. Total snow density encompasses all constituents of snow (ice, liquid water, and air) while dry snow density refers to the ice matrix and air only.

2.23
snow depth
the total height of the *snowpack*, measured vertically from the base to the *snow surface*

Note 1 to entry The slope-perpendicular equivalent of snow depth is the *snowpack thickness*.

2.24
snow distribution
spatial and temporal variability of snow cover affected by *snowfall*, wind speed, elevation, topography, vegetation and ablation

2.25
snow erosion
the process by which the surface of the *snow cover* is worn away, primarily by the action of wind

Note 1 to entry Wind erosion is a very important factor in the *redistribution* of snow.

2.26
snow height
the vertical distance from a base to a specific level in the snow, or to the *snow surface*

Note 1 to entry Ground surface is usually taken as the base, but on *firn* fields and *glaciers* it refers to the level of either the *firn* surface or *glacier* ice. Height is used to denote the locations of layer boundaries but also of measurements such as snow temperatures relative to the base. Where only the upper part of the *snowpack* is of interest, the *snow surface* may be taken as the reference. This should be indicated by using negative coordinate values. *Snow depth* is the total height of the *snowpack*.

2.27
snow layer

a layer of ice crystals with similar size and shape

2.28
snow load
the downward force on an object or structure caused by the weight of *accumulated snow*

2.29
snow metamorphism
the transformation that the snow undergoes in the period from *deposition* to either melting or passage to glacial ice

Note 1 to entry Meteorological conditions as well as mechanical or gravitational stresses are the primary external factors that affect snow metamorphism.

2.30
snow pit
in this case a pit dug vertically into the *snowpack* where *snowpack stratigraphy* and characteristics of the individual *snow layers* are observed

Note 1 to entry See also *snow profile*.

2.31
snow profile
a *stratigraphic* record of the *snowpack* including characteristics of individual *snow layers*, usually performed in *snow pits*

2.32
snow sample
in this case a sample of snow with a defined volume extracted from the *snowpack*

2.33
snow sampler
an instrument used for the collection of *snow samples* in an undisturbed *snowpack*

2.34
snow season
the time period when the ground usually is covered by snow

2.35
snow surface
the uppermost part of the snow cover, forming the interface to the atmosphere

2.36
snow survey
the process of determining snow parameters, most often depth and density, at representative points, usually along a *snow course*

2.37
snow water equivalent (SWE)
the depth of water that would result if a certain amount of snow melted completely

Note 1 to entry It can represent the *snow cover* over a given region or a confined snow sample over the corresponding area. The snow water equivalent is the product of the *snow height* and the *snow density* divided by the density of water. It is typically expressed in millimetres of water equivalent, which is equivalent to kilograms per square metre or litres of water per square metre.

2.38
snowdrift

a mound or bank of snow deposited as sloping surfaces and peaks, often behind obstacles, irregularities, and on lee slopes, due to eddies in the wind field. (See also *deposition*)

2.39
snowfall
the quantity of snow falling within a given area in a given time

2.40
snowpack
the *accumulation* of snow on the ground at a given site and time; term to be preferably used in conjunction with the physical and mechanical properties of the snow

Note 1 to entry See also *snow cover*.

2.41
snowpack stratigraphy
the definition and description of the stratified, i.e. layered *snowpack*

Note 1 to entry See also *snow profile*.

2.42
snowpack thickness
the total height of the *snowpack*, measured perpendicularly from base to snow surface, i.e. at right angle to the slope on inclined *snow covers*

Note 1 to entry When observers report thickness, they should also include the slope angle with respect to either the *snow surface* or a layer within the *snowpack*, e.g., the bed surface of an avalanche. The slope-vertical equivalent of *snowpack* thickness is the *snow depth*.

2.43
sublimation
the change of state of matter from solid phase to gaseous phase without entering liquid phase (opposite of *deposition*)

3 Symbols

The symbols used in this technical report are given in Table 1.

Table 1 — Symbols

Symbol	Quantity	Most common units
SWE	Snow water equivalent	m, mm
D	Snow depth	m, cm
m	Mass	kg, g
ρ	Density	$kg \cdot m^{-3}$, $g \cdot cm^{-3}$
V	Volume	m^3, cm^3
A	Area	m^2, cm^2

4 Objective

4.1 Spatial estimation of SWE

Measurements of SWE are essential for estimation of the total snow water content in catchment areas. Manual SWE measurements made by meteorological observers are often used as a complement to precipitation measurements. In areas where water budget calculations are difficult, due to sparse meteorological networks, additional snow surveys may be required. This is the case especially in mountainous regions where precipitation at the measuring stations often badly represents the precipitation in the region.

SWE observations are used as input to and verification of models for calculation of river and ground water flow, water management, flood warnings, snow load assessment, avalanche prediction and glacier mass balance calculations.

Data from point measurements of SWE can be used to estimate the spatial distribution by means of a number of methods. These include the following which are described in more detail in clause 9.

Ground measurements can be spatially distributed by use of:

- mathematical regionalization algorithms;
- mean or weighted values from snow courses.

Ground measurements can be used for calibration, validation and updating of:

- meteorological and hydrological models;
- snow distribution models;
- remote sensing systems for snow monitoring.

4.2 Snow load assessment

Collapse of buildings/structures, due to excessive snow loads, is a serious problem both in terms of economic loss and public safety. The SWE present on roofs often differs a lot from the mean value in the landscape. Wind and snow creep together with the presence of taller buildings/structures are factors which can decrease or increase the weight of the snow on a certain building/structure. Measurement of SWE on roofs as well as on the ground can potentially be of vital importance.

4.3 Snow profile

Periods of melting and freezing, snow falling at different air temperatures, and wind packing the snow, result in layers of ice, crust, and snow with different densities. By digging a snow pit with a vertical wall, layers in the snow can be detected and measured separately.

Knowledge of layers with different density is essential in avalanche risk forecasting. Furthermore, it can be important for the correct assessment of the functioning of automatic measuring instruments.

4.4 Water content in newly fallen snow

Daily data on new snow measurements are very important for, e.g. military services, emergency and civil protection services, road and airport maintenance services, avalanche forecasting and tourism. Continuous registration of newly fallen snow can also be a complement to precipitation monitoring, and for verifying weather forecasts.

Usually the sampling is carried out by use of a snow measurement board, which is made from a thin board that will not sink into the snow, yet be heavy enough not to be blown away. The board should be pushed into the snow surface just far enough so that the top of the board is nearly level or slightly below the top of the old snow. Samples can be taken with a cylinder either at regular intervals or after each snowfall. After each observation the board should be cleaned and placed in a new location close to the previous sample points.

The snow measurement board may need daily observations to assure that the top remains flush with the old snow. To reduce the risk of heat absorption the board should be painted white.

The measuring site should be sheltered as much as possible from drifting and blowing snow.

4.5 Reference to automatic SWE measurements

A manual point measurement of the total value of SWE is regarded to give a more accurate value than any other measuring method, as the assessment of the quality of the measurement is made directly on site. Therefore the manual measurement is considered to be the reference standard method.

Layers in snowpack can act like bridges thus affecting the distribution of the weight of the snow on the site, which may lower or raise the pressure on weighing sensors detecting the snow mass. Another problem can be changes in homogeneity in the snowpack within very short distances, which typically occurs at the very end of the snow season. Furthermore, measurements can fail due to malfunction of the sensors, or failure of electronic circuits.

To ensure that readings of automatic sensors are as accurate as possible a quality control programme using manual measurements should be established. It may be appropriate to undertake frequent manual measurements following the initial installation of recorders to ensure correct performance of the instrument. When the reliability of the sensor is proven, the quality program can be less frequent.

5 Principle of manual SWE measurements

A manual point measurement of the total SWE is performed by taking a vertical core from the snow surface to the bottom of the snowpack, using a tube or core drill.

The water content of the snow in the sample is assumed to be the amount of snow that has fallen on the site, and is still left after occasional melting and blowing periods. Determination of the SWE in the sample is performed either by weighing (see Annex C) or melting (see Annex D) the snow.

The SWE profile of the snowpack is normally measured from the wall of a snow pit by use of a density cutter, with samples taken horizontally or vertically, but the principle of determination of density and SWE is the same.

See clause 8 for further explanation of the methods.

6 Measurement sites

6.1 General

The criteria for selection of SWE measuring sites are independent of the measuring method, and similar to siting precipitation gauges for measurement of snowfall.

Sites for both single point measurements and snow courses should be chosen to be representative of the area of interest.

Where the snow is distributed homogeneously over the area, a few single point measurements could be sufficient. In locations where snow depth and density changes are caused by wind drift, and interception play an important role, snow courses are recommended.

A totally open area where the distribution of snow is more affected by wind should if possible be avoided, as well as pronounced recesses and summits of the terrain.

If the total accumulation of snow mass is of interest, the site should be chosen at elevations and exposures where there is as little melting as possible prior to the peak accumulation;

Recommended locations of SWE measurement sites are:

— at places where the terrain is horizontal in order to minimize the affect from snow creep;

— at clearings in bush land and open forests sufficiently large so that snow can fall to the ground without being intercepted by the branches. Trees in the distance may be helpful in making a wind break, preventing snow drift, and thus providing for a more even distribution of the snow accumulation;

— at places sufficiently distant from larger trees, rock outcrops and buildings which could disturb natural accumulation and melting of the snow. The closest recommended distance between the sampling point and the nearest obstacle is roughly equal to the height of the obstacle;

— at places where the environment is rather constant over a long period of time. This will ensure that conditions on sampling sites remain consistent.

If the measurements are made for estimating the SWE in whole regions, sites where the temperature can be strongly unrepresentative should be avoided. This means that measuring sites should not be located in urban areas, or at locals where direct solar radiation or shadow could have considerable thermal influences.

Bogs should be avoided because of possible influence from water underneath and difficulty in measuring the accurate snow depth.

Hollows and gullies, ridges and tops should be avoided because of possible negative wind effects.

In order to avoid any systematic error because of drifting snow it may be necessary to perform extensive survey measurements prior to finally determining the location of measuring sites, and length and sampling distance for snow courses (9.3).

There is an advantage in installing SWE measuring stations at or close to meteorological stations since meteorological parameters are important for evaluation and validation of SWE, and vice versa.

NOTE Further recommendations can be found in the WMO Guide to Hydrological Practices No. 168.

6.2 Manual measurements

Manual measurements provide the possibility of controlling sources of error and assessment of the result directly in the field, which enables assurance of the data quality. A disadvantage is the low sampling frequency.

The ground can be irregular under the snowpack, and the snow depth, and thus the SWE, can vary within a short distance. If it is important for the measuring program that measurements always are carried out on the same spot, the measuring sites should be marked, or positioned by GPS.

To ensure continuity of the measurements the sites should be easily accessible even when the possibility of transportation in the terrain, or the weather, is bad. The personnel who perform the measurements should be well trained to carry out the measurements correctly, even under bad weather conditions.

Melting and freezing periods during the winter can result in layers of ice inside the snowpack. Problems might occur to penetrate thick ice layers with the sampler, and digging a pit to the ground could be necessary to identify the layers and measure them separately.

7 Measurements

7.1 General

Data on snow depth is often more requested then data on SWE, and is thus a more common parameter in national weather service and road service station networks. For calculation of SWE, however, the snow density is required. Equation 1 shows how SWE is calculated in a sampling point.

$$SWE = \frac{\rho_{snow}}{\rho_{water}} \times D$$

Equation 1

where:

SWE is the snow water equivalent (m)

ρ_{snow} is the snow density (kg·m^{-3})

ρ_{water} is the water density (1000 kg·m^{-3})

D is the snow depth (m)

If a SWE measuring site is situated close to a meteorological station, a model for calculation of SWE at the site can be set up, where the only input data required are the meteorological parameters and snow depth. It is recommended that at least 5 years of measurements of snow density and depth are used for model calibration.

7.2 Snow density

The density of a snow sample is the snow mass per volume unit of the undisturbed snow sample (Equation 2). The volume of the undisturbed snow sample is calculated by multiplying the snow depth at the sampling point with the inner area of the sampler. By the weighing method (Equation 3) the mass of the sample is determined by a balance or scale, and by the volumetric method (Equation 4) the mass of water is calculated from the volume of melted water of the sample, and the density of water.

$$\rho_{snow} = \frac{M}{V}$$

Equation 2

$$\rho_{snow} = \frac{M}{A \times D}$$

Equation 3

$$\rho_{snow} = \frac{V_{water} \times \rho_{water}}{A \times D}$$

Equation 4

where:

ρ_{snow} is the snow density (kg·m^{-3})

M is the mass of the snow sample (kg)

V is the volume of the undisturbed sample (m^3)

A is the inner cross-sectional area of the snow sampler (m^2)

D is the snow depth at the sampling point (m)

V_{water} is the melted water volume of the snow sample (m^3)

ρ_{water} is the water density (1000 $kg \cdot m^{-3}$)

The snow density at the site should be taken as the average of at least three density samples, taken close to each other. The deviation of each sample should not differ more than 10 % from their mean value; otherwise more samples should be taken until at least three samples are within the range. Samples outside the range may not be used in the calculation.

Calculation of the snow density gives an indication of the quality of the measurement since the value should be within an expected range. Typical values of a late winter snowpack are often between 250 $kg \cdot m^{-3}$ to 450 $kg \cdot m^{-3}$. The maximum range in nature is between 30 $kg \cdot m^{-3}$ in very dry new snow to 600 $kg \cdot m^{-3}$ in very wet or/and compact snow. However, in very thick snow layers, for example on glaciers or high alpine areas, densities above 600 $kg \cdot m^{-3}$ are possible.

7.3 Snow depth

7.3.1 Manual probing

For manual measurement of snow depths up to 1,5 m a graduated stick can be used. In deeper snow it is preferred to use a so-called avalanche probe, made up by several metal rods which connected together normally has a total length between 2 m to 4 m.

Additional snow depth measurements during snow surveys will give a better spatial estimation of the SWE, if estimation of snow density at the depth measurement points is possible. Manual measurement of the snow depth is much easier, less time consuming, and cheaper than measurement of density. Therefore a frequent sounding during the survey can be cost effective.

Manual probing can also be necessary for verification of snow depth measurements performed with other methods, and for checking the snow depth prior to SWE measurements (see clause 8).

7.3.2 Manual readings on fixed snow stakes

A common method for the determination of snow depth is by the use of fixed stakes (see Annex E). The entire length of a snow stake should have a graduated scale with the zero point exactly at the ground level. This enables readings to be taken from a distance without disturbing the snow surface close to the stake. Whilst taking measurements from the snow stake it is important to survey against the surrounding snow surface from a horizontal position.

A snow stake should be painted white to minimize undue melting of snow around the stakes caused by absorption of solar radiation. If doubt exists about the reading, due to snow drift or ablation around the stake, the true snow depth should be checked using an independent measuring device.

It is important that the snow close to the stake is left untouched. Therefore, it is recommended to approach the site always from the same direction. Any snow pits should be filled after measurement.

7.3.3 Automatic recording

Automatic measurements of snow depth make it is possible to follow the snow accumulation and ablation in detail. Today acoustic and optoelectronic sensors mounted above the snowpack can be purchased.

Acoustic (ultrasonic) instruments measure the time interval from when the transmitted ultrasonic pulse is sent until its reflection against the snow surface is received.

Optoelectronic (laser) sensors use optoelectronic principles. Eye-safe visible laser is emitted against the snow surface. Reflected light is received, and from the phase shift the distance to the snow is calculated.

7.3.4 Remote sensing

Laser scanning provides spatial snow depth measurements covering large areas in inaccessible terrain. The measurements can be airborne (ALS, Airborne Laser Scanning) and ground-based (TSL, Terrestrial Scanning Laser).

With ground penetrating radar (GPR) large lateral distances can be measured in a short period of time. Normally, the two-way travel time for radar waves is measured and converted into snow depth or SWE estimates. The measurements can be either air-born (e.g. from a helicopter) or ground based (e.g. from a snowmobile).

8 Manual SWE sampling methods

8.1 General

Generally, weighing of the snow sample is accomplished by means of a spring scale or by a special balance. The spring scale is the most practical approach as it is relatively useful even in strong wind. However, spring scales used for snow measurements in field are accurate only to about 5 g -10 g, and the error in weighing by this method may be appreciable for small diameter samplers and shallow depths of snow. Scale balances, potentially more accurate, are very difficult to use under windy conditions.

Another approach is to store the samples in sealed plastic containers or bags and return them to a base station where they may be accurately weighed or melted and measured with a graduated cylinder. In practice, this procedure is difficult to carry out as the samples should be bagged without loss, carefully labelled, and carried back to the base. The advantage of measurement in the field is that any gross errors due to plugging the sampler, or losses due to part of the sample falling out, may be readily recognized, and repeat readings can be taken at once.

The results may be recorded on site with other pertinent observations and, if a good notebook is used, there can be little chance of confusion as to the location or the sampling conditions. In all measurements of this type, the extremely difficult physical conditions under which observations should frequently be made should always be kept in mind, and practical consideration should prevail in sampler designs.

Snow can easily freeze inside the sampler. This is often a problem when the equipment has been stored warm before the measurement. Therefore the measurement should not start until the sampler has the same temperature as the air. Preparation of the inside of the sampler with silica spray prior to the sampling may reduce the build-up of ice. Using the silica on the outside may make penetration of the snowpack easier.

A list of samplers is shown in Annex F. The table includes the operator, dimensions, material and the approximate cost of the equipment.

8.2 Snow tubes

Snow tubes (see Annex G) are used for measurement of the SWE of total snowpack from the snow surface to the ground. The sampling can be performed without digging and is hence carried out quickly. Normally, about 30 - 60 samples can be taken during an eight hour working day under normal snow conditions, if the snow depth is less than 2 m and the sampling sites are easily accessed.

Most snow tubes are made of aluminium, stainless steel, PVC or fibreglass. The tube is graduated on the outside for reading of the snow depth. A sharp edged cutter at the lower end facilitates insertion into the snow, especially if there are harder crust layers inside the snowpack. If the edge of the cutter consists of sharpened saw teeth even relatively thick ice layers can be penetrated. Small diameter cutters retain the sample much better than large cutters, but larger samples increase the accuracy in weighing.

Prior to the measurement the snow depth should be checked by sounding. This enables to choose the correct length of sampler to be used, and makes it possible to identify hard crust and ice layers in the snow pack which otherwise could be mistaken for the ground.

In order to cut the core, the sampler is forced vertically downward through the snow cover until it reaches the ground. If snow conditions permit, a steady downward thrust, causing an uninterrupted flow of the core into the tube, is best. A minimum amount of turning the tube is possible without interrupting the downward thrust. This brings the cutter into play, which is desirable for quick penetration of thin ice layers.

After reaching the ground the sampler can be turned a last time to force some soil into the cutter. The snow depth is obtained by reading on the ruler on the snow sampler, after which the sampler should be pulled up gently. A soil plug can prevent loss of core through the cutter while the sampler is withdrawn, and indicates that the whole snowpack has been penetrated. Any soil, though, should be removed from the sample and its depth excluded from the total measured depth. On wetland sites it may be difficult to feel when the sampler has reached the ground, if it is not frozen, and the tube may go relatively deep into the soil.

In order to prevent loss of core through the cutter while the sampler is withdrawn from the snow, sufficient soil can be gathered in the cutter to serve as a plug. The extent to which this will have to be done depends on the condition of the snow. The inside of the cutter can be conic-shaped, and the inner diameter of the tube a little larger than the inner diameter of the cutter. It can also help to compress the snow from the upper end of the tube by use of a rod.

If the snowpack is thicker than the length of the tube, an adjacent pit should be dug to the level where the mouth of the sample is situated. The next sample is taken from this level to the ground. If the ground is not reached this procedure is repeated.

To enable measurements in very deep snowpack snow tubes can be made in sections which can be connected together.

Normally, the SWE is calculated by weighing the snow samples, either by weighing it together with the sampler or by pouring the snow into for example a bag or bucket and weighing it separately (see Annex C).

A cylindrical brush mounted on a thin shaft can be used for cleaning the inside of the tube between the measurements.

8.3 Core drills

If the snow is very deep and the density is high, measurements with snow tubes may be very difficult and time consuming. Use of core drills (see Annex H) may be preferred when the snow depth exceeds 3 m - 4 m. This method is mainly used for taking samples from glaciers.

When measuring on glaciers it is recommended that a snow pit is dug to identify the bottom of the snow layer of the last season.

To be able to use a core drill, the snow should be hard enough to prevent the sample from falling apart and it may be necessary to dig a pit to the depth of between one and one and a half metres to reach suitable snow conditions. The snow layer from the surface to the bottom of the pit is measured traditionally with a snow tube or density cutter. From the bottom of the pit a core is taken vertically until the whole snow layer is penetrated.

8.4 Density cutters

The density profile of a snowpack can be detected by taking samples with density cutters (see Annex I). There are different styles of cutters on the market:

- wedge-type cutters
- box-type cutters
- tube-type cutters

Density profile measurements provide a visual examination of the layers during the measurement, and different layers are measured separately.

The wedge-type and box-type cutters should be inserted horizontally to the wall of the pit. The samples should cover the whole depth of the snow pit, with a slight overlap (see Annex I).

When measuring with a cylinder tube a thin board is inserted horizontally at a chosen depth into the edge of the pit. The cylinder is pushed vertically through the snow until it reaches the board and the depth of the sample is recorded. The sample is taken up supported by the board and the mass of the sample is measured. The board is inserted again at a selected depth under the previous sample and the procedure is repeated until the whole snow layer has been penetrated.

When measuring the whole snowpack, any ice on the ground surface, which is not caught in the sample, should be measured and included in the result.

If thick ice layers make snow tube measurement impossible, the method described for tube-type cutters can be applied to the snow tube measurement.

9 Spatial estimation

9.1 General

A challenge concerning spatial distribution of point measurements is to provide the optimal strategy that leads to the most accurate estimation. A number of techniques are used for direct distribution of point measurements of SWE including interpolation methods, snow courses and regression modelling.

Indirect distribution of SWE ground measurements is made by models and remote sensing techniques which uses ground-based measurements for calibration and validation.

9.2 Interpolation methods

Mathematical regionalization algorithms are used to transfer point measurements of SWE to areal estimates. This interpolation is performed according to ordinary stochastic methods. Quality differences between interpolation in open areas, forests and mountain areas cannot be avoided. Therefore a particularly detailed analysis of the weighting of single-point measurements should be considered before the interpolation of SWE data.

The following methods are most common:

- Thiessen-polygons;
- inverse distance weighting;
- kriging.

Thiessen-polygons define individual areas of influence around each of a set of points. Thiessen-polygons are polygons whose boundaries define the area that is closest to each point relative to all other points. They are mathematically defined by the perpendicular bisectors of the lines between all points.

Inverse distance weighting interpolated estimates are made based on values at nearby locations weighted only by distance from the interpolation location. No assumptions about spatial relationships are included except the basic assumption that nearby points ought to be more closely related than distant points to the value at the interpolate location.

Kriging is a method in which interpolation estimates are made based on values at neighbouring locations plus knowledge about the underlying spatial correlations in a data set. Variograms provide knowledge about the underlying relationships. Kriging is usually superior to other means of interpolation because it provides an optimal interpolation estimate for a given coordinate location, as well as a variance estimate for the interpolated values.

9.3 Snow courses

A snow course is a trail along which snow depth and density measurements are performed, often with considerably fewer density measurements. The selection of sites for snow courses depends on the purpose of the measurement. For example, when the data is to be used as an index parameter for correlation of physical parameters, a different site may be more appropriate than when an absolute SWE value for a specified catchment area is desired.

To represent the total water volume in an inhomogeneous landscape the locations of the courses should be chosen to cover the variability of the snow distribution and precipitation conditions at specific elevations, terrain types, ground inclinations and cardinal directions. While the snow depth varies a lot more than the snow density, additional depth soundings should be performed to ensure a representative value of the total SWE.

The more inhomogeneous snow conditions along the snow course the longer it should be. Usually a snow course consists of 5 - 50 depth soundings and 3 measurements of density taken along the course, preferably at different snow depths. For courses longer than 1 000 m density samples should be conducted at least every 500 m. The greater the snow depth variability the more depth samples should be conducted. Their location will depend on the site conditions, and the local knowledge of the observer. The snow depth samples should be conducted mainly along the snow course, but further samples in a perpendicular direction are useful for taking any lateral variations into account.

It is preferable to have stationary snow stakes with graduated scales along snow courses, but often it is not practicable due to the high number of sampling points. Nevertheless, the sampling sites can be marked on nearby trees or with sticks. If the snowpack at the site is very homogeneous along the trail, measurements can be done with enough accuracy by using a compass and a rope for determination of the distance, or by GPS positioning.

SWE data from snow course measurements can be attributed to the whole catchment area by use of mean values of snow courses/sampling points in the area, interpolation methods (9.2) and regression modelling (9.4).

9.4 Regression modelling

Regression methods for data distribution are preferred to interpolation methods if topographic variables, which are independent to each other, have a significant influence locally on the amount of precipitation, snow accumulation and ablation.

Such topographic variables include:

- elevation;
- forest - open field;
- easting - southing;

- slope inclination;
- slope aspect;
- shadow;
- curvature;
- wind exposure.

Regression models can be used for spatial distribution of point and snow course measurements, as well as for the selection of measuring sites and snow courses.

Regression modelling and interpolation methods can be applied in combination. Anomalies at station locations can be estimated by regression and then put into an interpolation algorithm.

9.5 Hydrologic and land surface modelling

A number of meteorological/hydrological and land surface models based on some of the most important meteorological input parameters incorporate snow in their algorithms. The approaches to model snow in these algorithms range from the very simple to the very complex, depending on the respective purposes of the models.

The models are classified into deterministic and stochastic models separated by the use of randomness in its calculations. Deterministic models given a particular input always produce the same output, while stochastic models incorporate the statistical nature of hydrology in their analysis. However, deterministic models can also have a certain degree of stochasticity.

Both deterministic and stochastic models can be based on empirical and physical algorithms. Empirical models are using simplified and experimentally derived relationships such as linear regressions. Physically based models are derived from more elaborate relationships, for example describing conservation of mass, momentum, and/or energy. The models can also use combinations of empirical and physically based equations.

Further, the models are subdivided with respect to their ability to handle spatial information. Lumped models spatially average the variables in the whole basin, while distributed models consider the spatial distribution of the variables by dividing the basins into sub-areas with unique properties. These sub-areas may either be so-called hydrological response units (sub-catchment areas) or square grid elements. Processes with a characteristic length scale smaller than the grid/element size are assumed to be represented implicitly (i.e. parameterized), while processes with length scales larger than the grid size are represented explicitly by element-to-element variations.

A higher resolution into sub-areas increases the possibility to use ground-based observations (for example SWE) in calibration and validation procedures.

Some hydrological and land surface models include snow distribution algorithms, taking into account the topographic influences on snow drift and ablation, which can be of high importance especially in alpine terrain.

9.6 Remote sensing systems for snow monitoring

Airborne and space-borne microwave sensors can monitor characteristics of snow cover, such as SWE, regardless of lighting conditions, time of the day, and vegetation. The snow parameters are extracted from the radar data by empirical algorithms, which are continuously evaluated and improved by use of in-situ observations as reference. Microwave remote sensing techniques can be divided into two categories: passive and active remote sensing.

Passive microwave remote sensing uses the radiation that is emitted from the underlying ground surface and transmitted through the snow layer into the atmosphere. The snowpack structure affects the amount of energy received at the sensor, thereby permitting estimates of SWE from brightness temperature values. Active microwave remote sensing devices work by emitting a signal of some sort, and then by processing the return of the signal.

Air-born gamma-ray SWE measurements are made, for example by the US National Weather Service. These measurements are passive remote sensing. By comparing the gamma-ray count rate for a survey with snow with the count rate obtained when there is no snow the SWE can be estimated.

The development of remote sensing systems will increase the need of ground-based automatic and manual SWE reference measurements for systematic validation of the data and calibration of measuring algorithms. The reference measurements should be spatially distributed to the scale of the remote sensing sensor.

10 Maintenance

All measuring equipment should be checked and cleaned as close to the start of the winter season as possible.

For measuring sites it is important that the area is inspected for changes and the zero point of the ruler should be confirmed to be exactly at the ground level. Vegetation should be removed if it is assumed that it will affect the snow accumulation. The ground where the snow samples will be taken should be clear of rock stumps and brush for a distance of more than two metres in all directions from where the samples will be taken. If necessary, high grass should be cut if it could affect the measurement and the accumulation of snow.

The observer should read the operating instructions at the start of the winter season. Training of field measurement personnel should be carried out regularly.

11 Uncertainties

11.1 Environmental factors

A measuring site with good correlation to the surroundings can be very difficult to find, and in addition several years of measurement are required to verify the representativeness of the results.

A changing environment, such as growing trees and new buildings close to the measuring site, could change the representation and homogeneity of the site. Maintenance of the measuring site is important to ensure the accuracy of the measurements.

Changes of prevailing wind direction, air humidity and temperature could change the distribution patterns of snow from one year to another.

Diurnal changes in the snowpack during strong metamorphism and melting causes the SWE to vary over short distances which often makes single point measurement unrepresentative during melting periods.

Snow tubes often underestimate SWE when ice lenses are present because the snow under the hard layer is pushed away before the cutter has penetrated the layer.

Wet snow in the samples is often a problem when the air temperature is below 0 °C, since ice can be built up inside the sampler.

11.2 Technical factors

Maintenance of the equipment is important. To minimise over or under-sampling care should be taken to use tubes with a sharp cutting end.

Snow can get stuck inside the sampler during the measurement. Treatment with wax, silicon or Teflon can help. If the sampler has not been kept cold enough prior to the measurement snow may melt and refreeze on the wall inside. If the sampler is weighed together with the sampler its tare weight should be checked from time to time and corrected if necessary.

11.3 Human factors

The most common errors associated with manual SWE measurements are mistakes due to the human factor, which tend to increase under extreme weather conditions. Snow course measuring methods require physically strong field personnel for measurements and maintenance of remote snow course sites.

12 Assessment of quality

Prior to further use of the measurement data of SWE, following quality checks are recommended:

- The range of values for snow depth and snow density should be tested.
- The measured data should be compared to the data of previous surveys.
- The measured data should be compared with data of neighbouring stations.
- The measured data should go through plausibility tests, especially in context with observations of precipitation, temperature and wind speed.

13 Measurement uncertainty

The uncertainty of the most important parameters during a manual measurement of SWE should under normal circumstances fall within following intervals:

- sampler/sample diameter ± 2 mm;
- snow depth ± 2 cm;
- sample weight ± 5 g -10 g (depending on the range of the scale);
- melted water volume ± 10 cm^3.

14 Recommendations

Due to the possibility of quality assessment during sampling, a manual point measurement is regarded as the reference method to all other methods and techniques for the measurement and estimation of SWE.

Remote sensing measurements of SWE are under development, but the resolution of the data is still poor and manual snow surveys are considered to give the best estimation of SWE in single drainage basins.

Snow surveys are often required to be performed in remote areas and personnel may have to travel long distances over difficult terrain, which often restricts the measurements to be carried out only a few times a year, sometimes only once a year, during the peak of accumulated snow.

In areas where the snow conditions are homogeneous, automatic measurements of snow depth, snow mass and SWE allow continuous recording of the parameters, but checks by manual measurements on a regular basis are preferred. If measurements performed on a weekly to monthly basis are sufficient, then a measuring program with manual measurements can be the most cost-effective method.

The instruments used for manual measurements can be very simple and cheap and are often produced by the users themselves. However, specialized manufacturers have developed instruments which withstand very rough handling and can be used under more extreme conditions and in deep snow.

Annex A
(informative)

List of methods for determination of SWE in total snowpack

Techniques	**Measuring area or distance**	**Fixed (F)** **Mobile (M)**
Manual measurement		
Single point	10 cm^2- 300 cm^2	M
Snow course	1 km/day - 5 km/day	M
Snow mass registration devices		
Snow pillow	2 m^2 - 10 m^2	F
Snow plate	2 m^2 - 25 m^2	F
Weighing lysimeter	10 m^2 - 25 m^2	F
Radioactive attenuation		
Gamma ray: active source	1 m^2	F
Gamma ray: cosmic radiation	1 m^2	F
Neutron probe	1 m^2	F
Electrical properties		
SPA station 1)	2 m-10 m	F
GPR station 1)	1 m^2	F
GPR mobile	20 km/day - 200 km/day	M

1) Snow Pac Analyzer (SPA). An instrument which allows automatic and continuous measurement of all the relevant snow parameters like snow depth, snow density, snow water equivalent and contents of liquid water and ice.

2) Ground Penetrating Radar (GPR). A geophysical method that uses radar pulses to image the subsurface such as snowpack.

Annex B
(informative)

Manual SWE measuring bodies in Europe

Measuring body	**Number of snow depth stations (app.)**	**Snow depth data available since** [1)]	**Number of SWE stations (app.)**	**SWE data available since** [1)]
Vattenregleringsföretagen, Sweden	50	2010	50	2010
Deutscher Wetterdienst, Germany	1950	1900	500	1950
Bundeswehr Geoinformation Service, Germany	20	1990	10	1995
Hochwasservorhersage-zentralen der Bundesländer, Germany	100	1985	80	1990
Lawinenwarndienst Bayern, Germany	20	?	20	?
Institut für Schnee- und Lawinenforschung, Switzerland	168	?	168	?
Hydrographischer Dienst, Zentralanstalt für Meteorologie und Geodynamik, Kraftwerksbetreiber, Austria	1008	1895	83	1921
Český hydrometeorologický ústav, Czech Rep.	785	1895	772	1926
Slovenský hydrometeorologický ústav, Slovakia	550	1921	550	1951
[1)]…The year of the first installation.				

Annex C
(informative)

Determination of mass of snow sample

The mass of the snow sample should be determined by use of an accurate calibrated weighing scale. The resolution of the scale should not exceed 10 g. Most commonly the sample is weighed hanging by use of spring scales, digital scales and steelyard scales. The snow sample can either be weighed by pouring it out from the sampler into a container such as plastic bag (1) or bucket (2) or by weighing the sample together with the sampler (3 and 4). The weight of the container/sampler should be taken into account.

Key

1 Weighing of snow sample in plastic bag

2 Weighing of snow sample in bucket

3 Horizontal weighing of snow sample in sampler

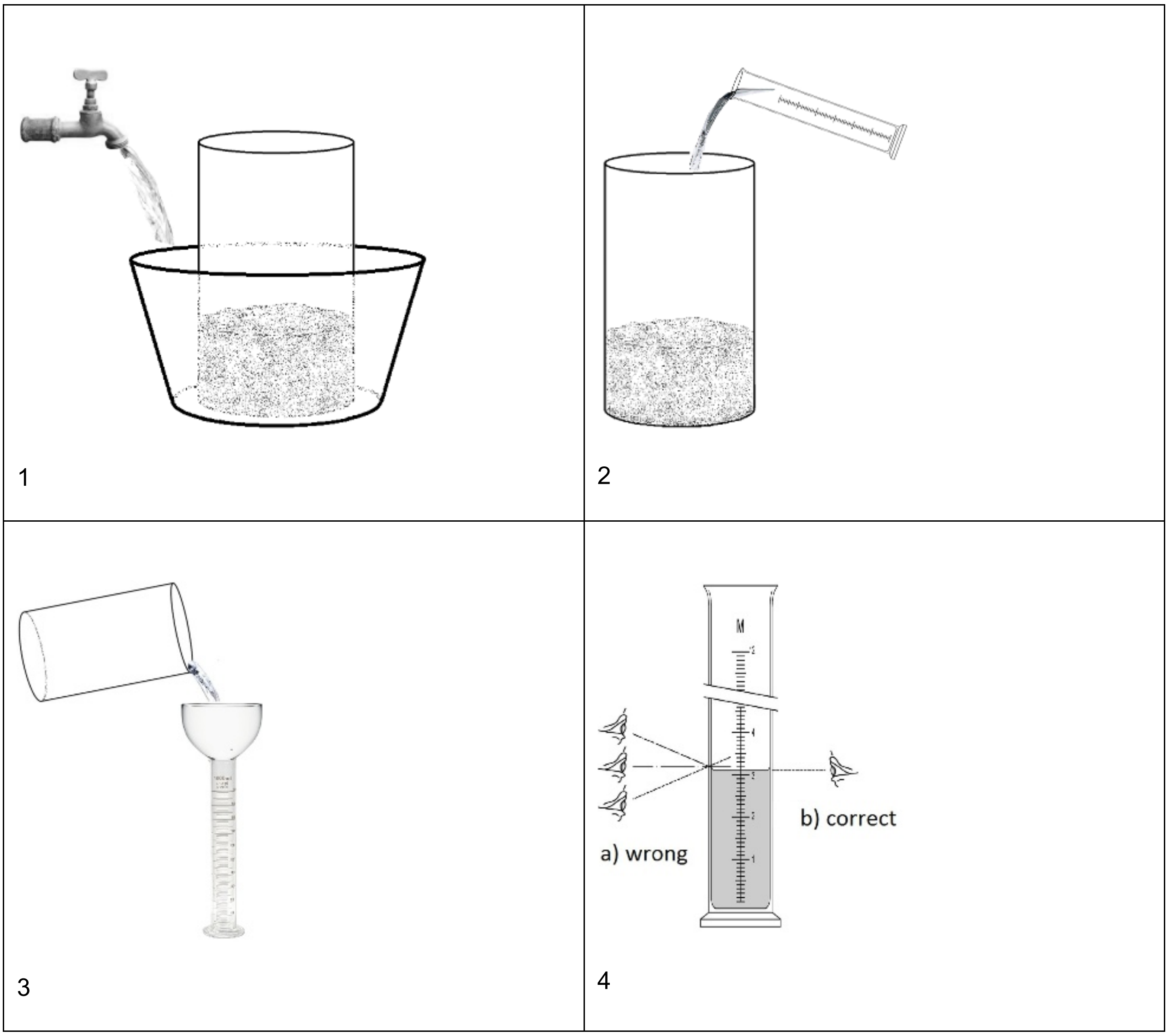
4 Vertical weighing of snow sample in sampler

Figure C.1 — Weighing of snow sample

Annex D
(informative)

Determination of water volume in snow sample

The volume of water in the sample is determined after melting the snow. To reduce the melting time the sample can be placed into a vessel which is lowered into a tank with warm water (1), or warm water with a known volume can be added to the vessel (2). The melted sample is poured into a measuring cylinder (3) and the volume is read using the lower part of the meniscus (4b). 4a) shows wrongly performed readings: when the observation is made from the upper part of the meniscus, or from above or below the horizontal line.



Key

1 Warm water outside the vessel

2 Warm water inside the vessel

3 Melted sample poured into measuring cylinder

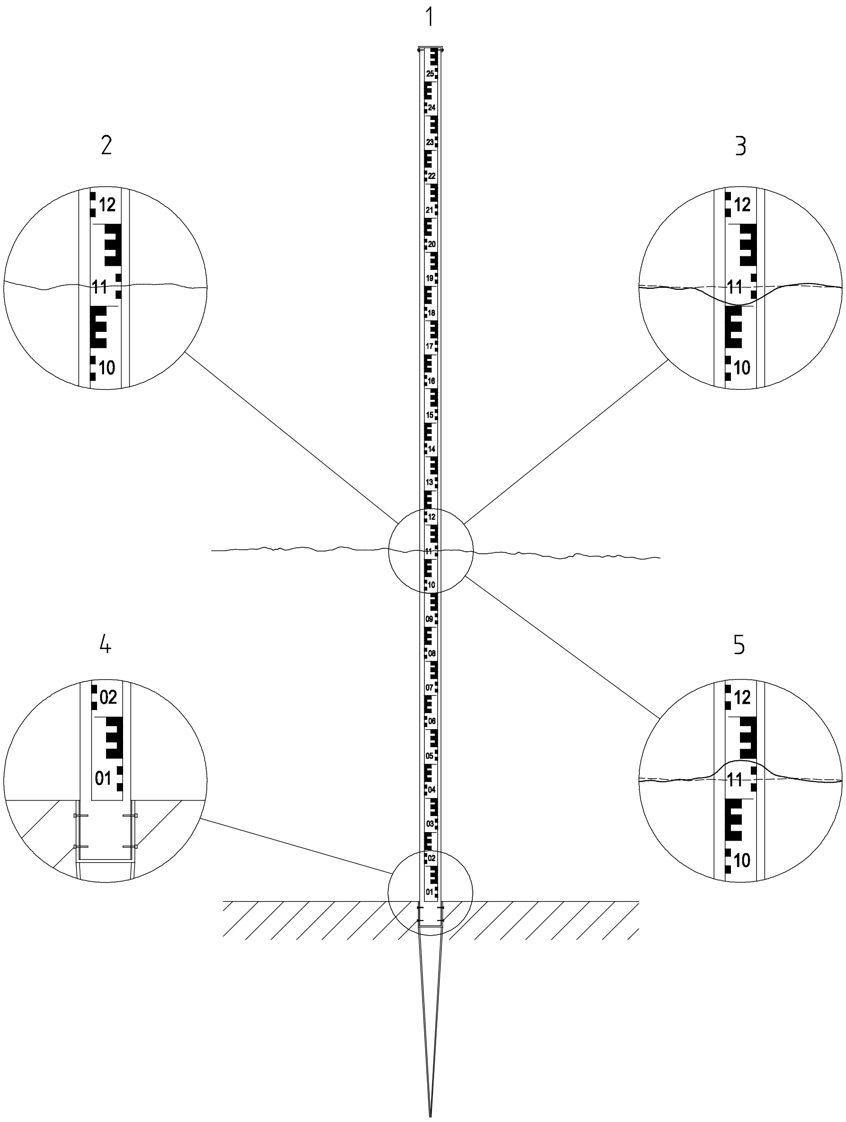
4 Reading on measuring cylinder

Figure D.1 — Determination of water volume in snow sample

Annex E
(informative)

Snow stakes

The snow stake (1) should be firmly established in the ground with the zero point of the scale exactly at the ground surface (4). The level of the snow surface is read directly on the scale (2). Care should be taken to avoid errors resulting from snow drift or ablation around the marker (3 and 5). If there is any doubts about the reading, complementary depth samples should be taken.



Key

1 Snow stake

2 Snow surface

3 Too low reading

4 Zero point

5 Too high reading

Figure E.1 — Snow stake

Annex F
(informative)

List of samplers for detection of SWE

Operator	Length (m)	Inner area (m^2)	Material	Mouth type	Approx. cost [1] (€)
Vattenregleringsföretagen, Sweden	1,0 .1,5 .2,0	0,0010 [2]	PVC	Stainless steel, sharp edge	350-400
Vattenregleringsföretagen, Sweden	0,83 per section (tot. max 4.15)	0,001116 [3]	Duraluminium	Stainless steel, cutting teeth	4500
Deutscher Wetterdienst, Bundeswehr, Hochwasservorhersagezentralen, Germany (standard instrument)	0,6	0,0050	Stainless steel	Stainless steel, cutting teeth	450
Deutscher Wetterdienst, Germany	1,0. 1,5	0,0050	Fibreglass	Stainless steel, cutting teeth	190-230
Deutscher Wetterdienst, Germany	0,5 per section (tot. max 1,0)	0,0050	Aluminium	Stainless steel, cutting teeth	No longer manufactured
SLF, Switzerland	0,55	0,0070			
SLF, Switzerland	0,189	0,002642			
Czech Hydrometeorological Institute, CHMI, Czech Rep.	1,0. 1,5. 2,0	0,0050	Fibreglass	Stainless steel, cutting teeth	150-200

[1] Approximate cost for a fully equipped set of SWE sampling device.

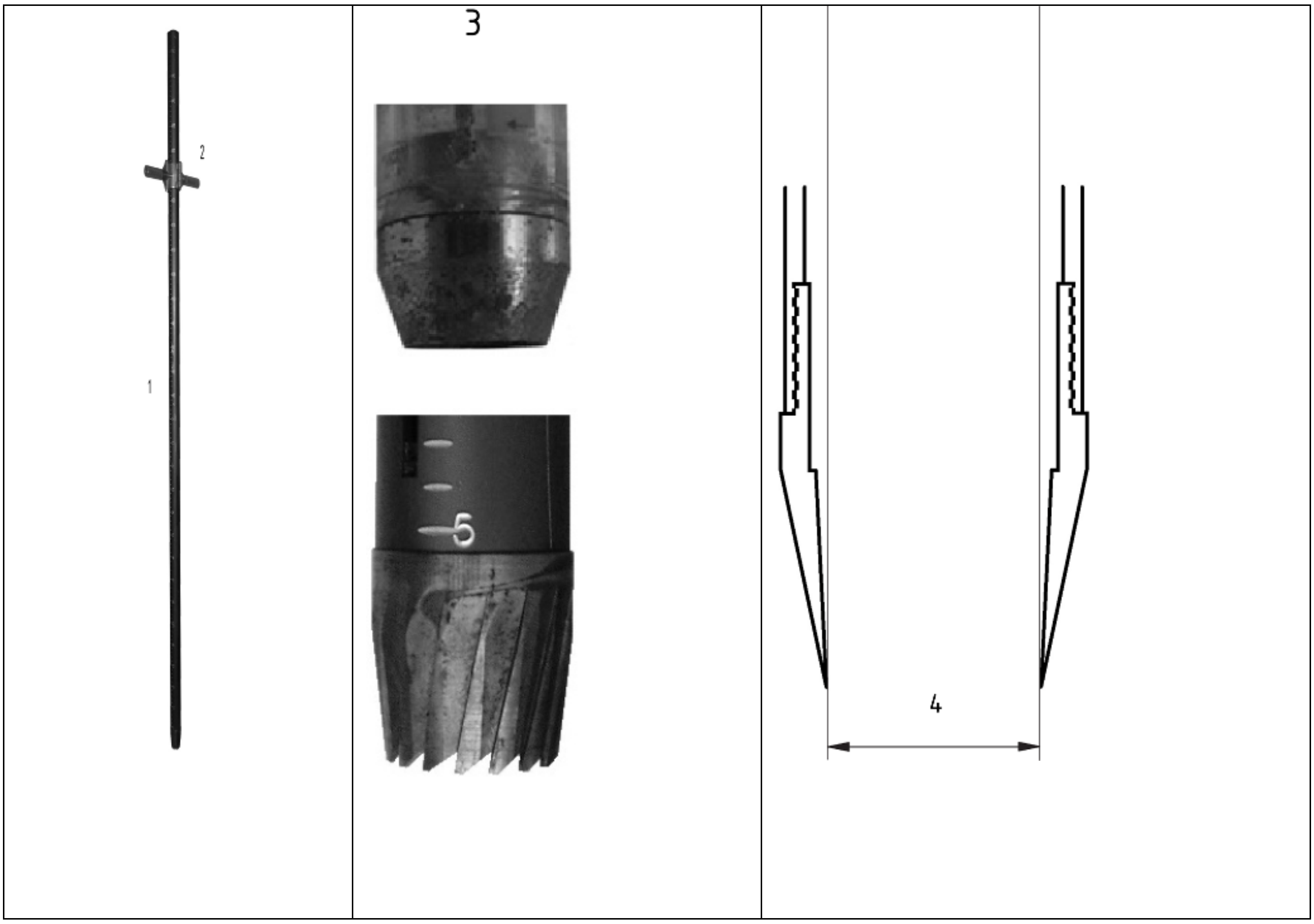
[2] The inner area of the instrument is chosen so that 1 g of snow in the sampler equals 1 mm SWE (metric system).

[3] The inner area of the instrument is chosen so that 1 ounce of snow in the sampler equals 1 inch SWE (imperial system).

Annex G
(informative)

Snow tubes

The sharp edge of the snow tube allows the penetration of hard snow layers in the snow pack. To prevent the snow in the tube from falling out when the sample is lifted up to the snow surface, the edge of the sampler should have a smaller inner diameter than the rest of the tube. A removable handle mounted on the tube facilitates sampling in deep snowpack, when the tube has to be heavily forced down into, and pulled up, from the snowpack.



Key

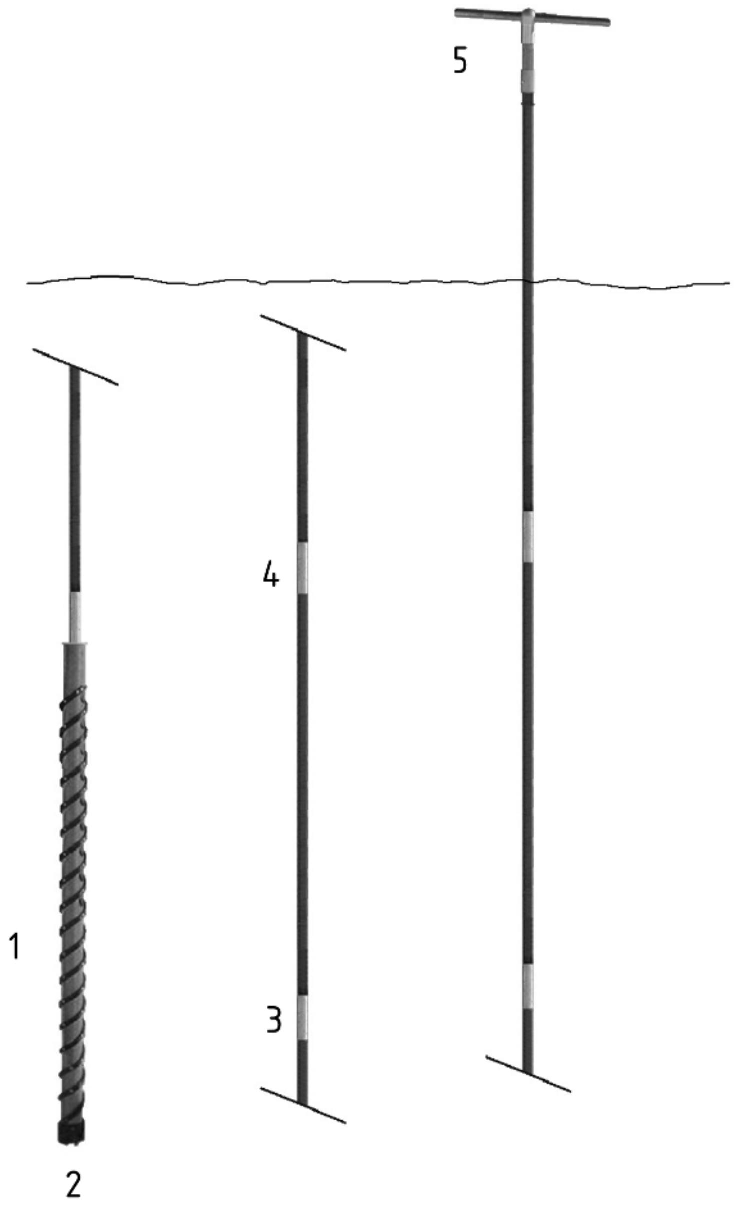
1. Snow tube
2. Handle
3. Sharp edged cutter bits
4. Sampler edge diameter

Figure G.1 — Snow tubes

Annex H
(informative)

Core drills

Core drills provides snow cores with a length of normally 0,5 m – 1,0 m. Samples after sample are drilled out until the desired depth is reached.



Key

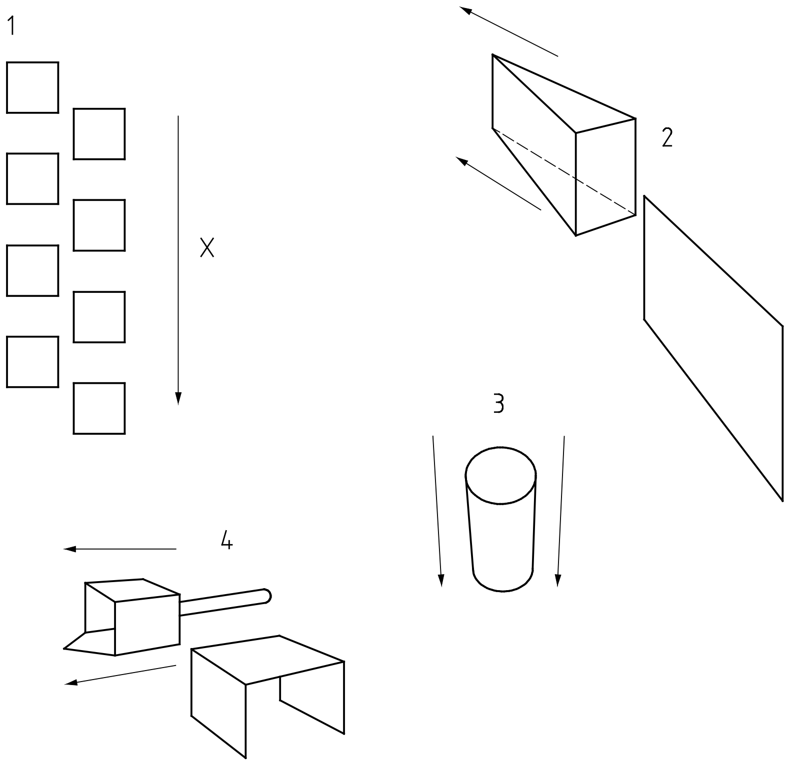
1 Core barrel
2 Core head
3 Extension
4 Drive adapter
5 “T”-handle

Figure H.1 — Core drill

Annex I
(informative)

Density cutters

To reduce the risk of high variability between samples caused by layering in the snow the tube-type cutter (2) should be inserted vertically cutting through the layers to a pre-placed spatula or board. The wedge-type (3) and box-type (4) cutters should be inserted horizontally to the wall of the pit with a slight overlap between the samples (1).



Key

X Snowpack depth

1 Overlapping density samples	3 Tube-type cutter
2 Wedge-type cutter	4 Box-type cutter

Figure I.1 — Density cutters

Annex J
(informative)

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