CHAPTER 7

MEASUREMENT OF PRECIPITATION

7.1 General

Precipitation is defined as the liquid or solid products of the condensation of water vapour falling from clouds or deposited from air on the ground. It includes rain, hail, snow, dew, rime, hoar frost and mist precipitation. The total amount of precipitation which reaches the ground in a stated period is expressed as the depth to which it would cover, in a liquid form, a horizontal projection of the earth's surface. Snowfall is also expressed by the depth of fresh snow covering an even horizontal surface.

Any method of measuring precipitation should aim to obtain a sample representative of the true amount falling over the area which the measurement is intended to represent. The choice of site, as well as the systematic measurement error, is therefore important (WMO, 1982; Allerup and Madsen, 1979; and Braslavsky *et al.*, 1975).

7.1.1 *Units and time of measurements*

The units of precipitation are linear measures. Daily amounts of precipitation should be read to the nearest 0.2 mm and, if feasible, to the nearest 0.1 mm; weekly or monthly amounts should be read to the nearest 1 mm (at least). Daily measurements of precipitation should be made at fixed times.

7.1.2 *Precipitation gauges*

Precipitation gauges are the most common instruments used to measure precipitation. Generally an open receptacle with vertical sides is used, usually in the form of a right cylinder. Various sizes and shapes of orifice and gauge height are used in different countries, so the measurements are not strictly comparable. The amount of precipitation caught in a gauge is measured using a graduated stick to determine the depth or by measuring the volume of, or weighing, the contents. The gauge orifice may be at one of many specified heights above the ground or it can be level with the surrounding ground. For gauges above ground-level, the orifice must be placed above (*a*) the maximum expected depth of snow cover; and (*b*) the height of significant potential in-splashing from the ground. Ground-level gauges are used only to measure liquid precipitation; they are placed in a pit with the gauge rim at ground level at a distance of 0.6 m from the nearest edge of the pit. A strong plastic or metal anti-splash grid with a central opening for the gauge should span the pit. Provision should be made for draining the pit.

The standard gauge orifice is horizontal. An orifice parallel to the slope of the ground may be used in hydrological studies. The gauge should be mounted firmly so that it can withstand strong winds and maintain its orifice horizontal.

7.1.3 *Errors in precipitation measurement*

Both systematic and random errors are important in precipitation measurement. Systematic error is caused by several components. The largest is due to systematic horizontal and vertical average accelerations of the wind just above the orifice of elevated gauges, which prevents some precipitation particles from entering the gauge. Thus, the amount of precipitation caught by the gauge is smaller than the amount of incident precipitation. However, the amount of precipitation measured by the gauge may also suffer systematic error because of other components, including:

(*a*) Wetting of the internal walls of the gauge, the collector and the container;

(*b*) Evaporation of some of the water accumulated in the container;

(*c*) Splashing of raindrops from or into the gauge;

(*d*) Blowing of snow from or into the gauge.

Random errors are likely to arise from the use of inaccurate dip-rod measures, spilling of water when transferring it to the measure, leakage into or out of the gauge, observational errors, deformation or damage of the gauge or its rim, deviations of the orifice position from the horizontal, etc.

The size of random errors can be reduced by frequently and regularly checking the gauge and the measured values and by taking appropriate corrective action. In contrast, the components of systematic error are inherent in the method of measurement of precipitation; their individual magnitudes vary, depending on instrumental and meteorological conditions, from very small to significant values. Thus not all the components need to be taken into consideration for given gauge types, seasons and regions. For example, the use of a pit gauge reduces the loss of liquid precipitation due to wind field deformation; the evaporation loss can be reduced by placing oil in the receiver or by designing the gauge so that (*a*) only a small water surface is exposed; (*b*) its ventilation is minimized; and (*c*) the internal temperature of the gauge is maintained as low as possible. The wetting loss can be reduced by using a smooth surface on the internal surfaces of the gauge so that water does not adhere to it. A reduction of wetting and evaporation losses is obtainable by the use of gauges whose walls are continuously tapered from the cylindrical part of the collector to the conical funnel so as to omit the usual join. The internal surfaces should never be painted because cracks will appear later and cause increased wetting loss. However, use of an enamel finish baked onto a gauge made of steel is satisfactory. The external surfaces can be painted white to help reduce evaporation loss. Splash into and out of the gauge can be reduced by a suitable design of collector (Figure 7.1). Methods for correcting for systematic errors are discussed in 7.2.1.

7.1.4 *Gauge location*

The location of precipitation stations within the area of interest is important, because the number and locations of gauge sites determine how well the measurements represent the actual amount of precipitation falling in the area. For more detailed information see the WMO *Guide to Hydrological Practices* (WMO – No. 168), Chapter 3.

In choosing a site, the systematic wind field deformation above an elevated gauge orifice, as well as the effects of the site itself on the air trajectories, should be considered.

The effects of the former can be reduced by selecting a sheltered site, but not so sheltered that surrounding objects interfere sufficiently to cause a reduction of the precipitation collected. Preferably, however, the effects can be reduced by using a ground-level gauge for liquid precipitation or by making the airflow horizontal above the gauge orifice using the following techniques. These are listed in the order of decreasing effectiveness:

(*a*) In areas having homogeneous dense vegetation, the height of such vegetation should be kept at the same level as the gauge orifice by regular clipping;

(*b*) In other areas, by stimulating the effect in (*a*) by the use of appropriate fence structures;

(*c*) By using windshields around the gauge.

The effects of the site itself can give rise to local excesses and deficiencies of precipitation falling onto the site.

In general, objects should not be closer to the gauge than a distance twice their height above the gauge orifice. For each site the average vertical angle (*a*) of obstacles should be estimated, and a site plan made. Sites on a slope or on the roof of a building should be avoided. The surface surrounding the precipitation gauge can be covered with short grass or gravel or shingle, but hard, flat surfaces such as concrete should be avoided to prevent excessive in-splashing. Sites selected for measurement of snowfall and/or snow cover should be in areas sheltered from the wind as much as possible. The best sites are often found in clearings within forests or orchards, among trees, in scrub or shrub forests, or where other objects act as an effective wind-break for winds from all directions.

The fact that data analysis is made easier if the same gauges are used and if siting criteria are similar should be a serious consideration in the planning for networks.

The open exposure of shipboard raingauges poses problems for which no solution has yet been found (see 17.7.3).

7.2 Non-recording gauges

7.2.1 *Standard gauges*

An ordinary precipitation gauge used for daily readings usually takes the form of a collector placed above a funnel leading into a container. The size of the orifice of the collector is not critical for liquid precipitation, but an area of at least 200 cm^2 is required if other precipitation is expected in significant quantity. An area of 200 to 500 cm^2 will probably be found most convenient. Whatever size of collector is chosen, the graduation of the measuring cylinder or stick must, of course, be consistent with it. The most important requirements of a gauge are as follows:

(*a*) The rim of the collector should have a sharp edge and should fall away vertically inside and be steeply bevelled outside; the design of gauges used for measuring snow should be such that any tendency to constrict the orifice by accumulation of wet snow about the rim is small;

(*b*) The area of the orifice should be known to the nearest 0.5 per cent and the construction should be such that this area remains constant while the gauge is in normal use;

(*c*) The collector should be designed to prevent rain from splashing in and out; this can be done by having the vertical wall sufficiently deep and the slope of the funnel sufficiently steep (at least 45°). Suitable arrangements are shown in Figure 7.1;

(*d*) The container should have a narrow entrance and be sufficiently protected from radiation to minimize the loss of water by evaporation. Precipitation gauges for use in locations where only weekly or monthly readings are practicable should be similar in design to the type used for daily measurements but with a container of larger capacity and stronger construction.

Figure 7.1 – Suitable collectors for raingauges

7.2.2 *Storage gauges*

Storage gauges are used to measure total seasonal precipitation in remote and sparsely inhabited areas. Such gauges consist of a collector above a funnel, leading into a container large enough to store the seasonal catch (or the monthly catch in wet areas).

An anti-freeze solution may be placed in the container to convert any snow which falls into the gauge to a liquid state. It is important that the anti-freeze solute remain dispersed. A mixture of 37.5 per cent by weight of commercial calcium chloride (78 per cent purity) and 62.5 per cent water makes a satisfactory anti-freeze solution. Alternatively, aqueous solutions of ethylene glycol or of a mixture of ethylene glycol with methanol can be used. While more expensive, the latter solutions are less corrosive than calcium chloride and give anti-freeze protection over a much wider range of dilution resulting from subsequent precipitation. The volume of the solution initially placed in the container should not exceed 33 per cent of the total volume of the gauge.

A layer of not less than 5 mm of a suitable oil or other evaporation suppressant should be placed in the container to reduce evaporation. This layer should allow free passage of precipitation into the solution below it.

The seasonal precipitation catch is determined by weighing or measuring the volume of the contents of the container. The amount of anti-freeze solution placed in the container at the beginning of the season and any contraction in the case of volumetric measurements must be carefully taken into account.

The operation and maintenance of storage gauges in remote areas pose several problems, such as capping of the gauge by snow, difficulty in locating the gauge for recording the measurement, etc., which require specific control. Particularly careful attention should be paid to assessing the quality of data from such gauges.

7.2.3 *Measurement methods*

Two types of apparatus are commonly used for measuring the precipitation caught in an ordinary (non-recording) gauge: a graduated measuring cylinder and a graduated dip rod. A measuring cylinder should be made of clear glass or plastic having a suitable coefficient of thermal expansion and should be clearly marked to show the size or the type of gauge with which it is to be used. Its diameter should be less than 33 per cent of that of the rim of the gauge; the smaller the relative diameter, the greater the precision of measurement.

The graduations should be finely engraved; in general there should be marks at 0.2 mm intervals and clearly figured lines at each whole millimetre. It is also desirable that the line corresponding to 0.1 mm be marked. The maximum error of the graduations should not exceed ±0.05 mm at or above the 2 mm graduation mark and ±0.02 mm below this mark.

To measure small precipitation amounts with adequate precision, the inside diameter of the measuring cylinder should taper off at its base. In all measurements, the bottom of the water meniscus should define the water-level and the cylinder should be kept vertical when reading, to avoid parallax errors. Repetition of the main graduation lines on the back of the measure is also helpful for reducing such errors.

Dip-rods should be made of cedar wood, or other suitable material which does not absorb water appreciably and possesses only a small capillary effect. Wooden dip-rods are unsuitable if oil has been added to the collector to suppress evaporation; in this situation, rods of metal or other materials from which oil can be readily cleaned must be used. Non-metallic rods should be provided with a brass foot to avoid wear and be graduated according to the relative areas of cross-section of the gauge orifice and the collector; graduations should be marked at least every 10 mm and should include an allowance for the displacement due to the rod itself. The maximum error in the dip-rod graduation should not exceed ± 0.5 mm at any point. A dip-rod measurement should be checked using a volumetric measure, wherever possible.

It is also possible to measure precipitation catch by accurate weighing, a procedure having several advantages. The total weight of the can and contents is measured and the known weight of the can is subtracted. There is no danger of spilling water and any water adhering to the can is included in the weight. The commonly used methods are, however, simpler and cheaper.

7.2.4 *Methods of adjustment for systematic error*

The amount of precipitation measured by commonly used gauges may be 3 per cent to 30 per cent less than the actual precipitation reaching the ground (or even less for solid precipitation). For many hydrological purposes it is necessary first to make adjustments to the data in order to allow for this condition prior to making calculations. The adjustments cannot, of course, be exact (and may even make things worse). Thus the original data should always be kept as the basic archive, both to maintain continuity and to serve as the best base for future improved adjustments if and when they become possible.

As the true amount of precipitation reaching the ground is not known, except in rare instances in which all the other items of the water balance are accurately known, the true amount of precipitation must be estimated by correcting for some or all of the various error terms listed below:

(*a*) Error due to systematic wind-field deformation above the gauge orifice;

(*b*) Error due to the wetting loss on the internal walls of the collector;

(*c*) Error due to evaporation from the container (most important in hot climates);

(*d*) Error due to the wetting loss in the container when it is emptied;

(*e*) Error due to blowing and drifting snow;

(*f*) Error due to the splashing-in and -out of water;

(*g*) Random observational and instrumental errors.

The first six error components are systematic and are listed in order of general importance. The net error due to blowing and drifting snow and due to splash-in and -out of water can be either negative or positive, while net systematic errors due to the wind field and other factors are negative. Since for liquid precipitation the errors listed as (*e*) and (*f*) above are near zero, the general model for adjusting the data from most gauges takes the following form:

$$P_k = kP_c = k\ (P_g + \Delta P_1 + \Delta P_2 + \Delta P_3) \qquad (7.1)$$

where P_k = adjusted precipitation amount;

k = adjustment factor for the effects of wind field deformation;

P_c = the amount of precipitation caught by the gauge collector;

P_g = the measured amount of precipitation in the gauge;
ΔP_1 = adjustment for the wetting loss in the internal walls of the collector;
ΔP_2 = adjustment for wetting loss in the container after emptying;
ΔP_3 = adjustment for evaporation from the container.

Full details of the models currently used for adjusting raw precipitation data in Denmark, Finland, Switzerland and the U.S.S.R. have been given in a review by Sevruk (WMO, 1982).

In general, the supplementary data needed to make such adjustments include the wind speed at the gauge orifice during precipitation, drop size, precipitation intensity, air temperature and humidity and characteristics of the gauge site. These data must be derived from standard meteorological observations at the site in order to provide daily adjustments. At sites where such observations are not made, interpolation between those observations made at adjacent sites may be used for making such adjustments, but with caution, and for monthly rainfall data only.

In all cases where precipitation measurements are adjusted in an attempt to reduce errors, it is strongly recommended that both the measured and adjusted values be published.

7.3 Recording gauges

Three types of precipitation recorder are in general use: the weighing type, the tilting or tipping bucket type, and the float type. Only the weighing type is satisfactory for measuring all kinds of precipitation, the use of the other two types being for the most part limited to the measurement of rainfall.

7.3.1 *Weighing type*

In these instruments the weight of a container together with the precipitation accumulating therein is recorded continuously, either by means of a spring mechanism or with a system of balance weights. All precipitation is thus recorded as it falls. This type of gauge normally has no provision for emptying itself, but a system of levers for the pen makes it possible to traverse the chart any number of times. The gauges should be designed to minimize evaporation losses, which can be accomplished by adding sufficient oil or other evaporation suppressant to the container to form a film over the water surface. Any difficulties arising from oscillation of the balance in strong winds can be reduced with an oil damping mechanism or, if recent work is substantiated, by suitably programming a microprocessor to eliminate this effect on the readings. Such weighing gauges are particularly useful for recording snow, hail, and mixtures of snow and rain, since the solid precipitation does not require melting before it can be recorded.

7.3.2 *Float type*

In this type of instrument the rain passes into a float chamber containing a light float. As the level of the water within the chamber rises, the vertical movement of the float is transmitted, by a suitable mechanism, to the movement of the pen on the chart. By suitably adjusting the dimensions of the collector orifice, float and float chamber, any desired chart scale can be used.

To provide a record over a useful period (24 hours is normally required) either the float chamber has to be very large (in which case a compressed scale on the chart is obtained), or a mechanism must be provided for automatically and quickly emptying the float chamber whenever it becomes full, so that the pen returns to the bottom of the chart. Usually a siphoning arrangement is used. The actual siphoning process should begin precisely on command with no tendency for the water to dribble over at either the beginning or the end of the siphoning period, which should not be longer than 15 seconds. In some instruments the float chamber assembly is mounted on knife edges so that the full chamber overbalances; the surge of the water assists in the siphoning process and when the chamber is empty, it returns to its original position. Other rain recorders have a forced siphon which operates in less than five seconds. One type of forced siphon has a small chamber separate from the main chamber which accommodates the rain that falls during siphoning. This chamber empties into the main chamber when siphoning ceases, ensuring a correct record of total rainfall.

A heating device (preferably controlled by a thermostat) should be installed inside the gauge if there is a possibility of the water in the float chamber freezing during the winter. This will prevent damage to the float and float chamber and will enable rain to be recorded during that period. A small heating element or electric lamp is suitable where a mains supply of electricity is available, otherwise other sources of power may be employed. One convenient method uses a short heating strip wound around the collecting chamber and connected to a large capacity battery. The amount of heat supplied should be kept to the minimum necessary to prevent freezing, because the heat may reduce the accuracy of the observations by stimulating vertical air movements above the gauge and by increasing evaporation losses.

7.3.3 *Tilting-bucket type*

The principle of operation is simple. A light metal container or bucket divided into two compartments is balanced in unstable equilibrium about a horizontal axis. In its normal position the bucket rests against one of two stops, which prevents it from tipping over completely. Rain water is conducted from a collector into the uppermost compartment and, after a predetermined amount has entered the compartment, the bucket becomes unstable and tips over to its alternative rest position. The bucket compartments are so shaped that the water is emptied from the lower one. Meanwhile subsequent rain falls into the newly positioned upper compartment. The movement of the bucket as it tips over can be used to operate a relay contact to produce a record consisting of discontinuous steps; the distance between each step on the record represents the time taken for a specified small amount of rain to fall. This amount of rain should not exceed 0.2 mm if detailed records are required.

The main advantage of this type of instrument is that it can be used for recording at a distance. Its disadvantages are:

(*a*) The bucket takes a small but finite time to tip over and during the first half of its motion additional rain may enter the compartment which already contains the calculated amount of rainfall. (This error, which can be appreciable during heavy rainfall, can be decreased by adding a device to accelerate the tipping action. Essentially, a small blade is impacted by the water falling from the collector and used to apply an additional force to the bucket, varying with rainfall intensity.)

(*b*) With the usual design of bucket the exposed water surface is large in relation to its volume so that appreciable evaporation losses can occur, especially in hot regions. This error will be most significant in light rain.

(*c*) The discontinuous nature of the record may not provide satisfactory data during light drizzle or very light rain. In particular, the time of onset and cessation of precipitation cannot be accurately determined.

A number of rainfall intensity recorders have been designed and used for special purposes; they are usually complex. A satisfactory record of rainfall intensity can be determined for many purposes from a float- or weighing-type recorder by providing adequate time resolution.

7.3.4 *Methods of recording*

Whether the rainfall recorder operates by the rise of a float, by the tipping of a bucket or by some other method, these movements must be converted into a form which can be stored and analysed later. The simplest method of producing a record is to move a time chart, by means of a spring- or electrically driven clock, past a pen which moves as the float or weighing device moves, or as a relay is closed. There are two main types of chart:

(*a*) *The drum chart.* This chart is secured around a drum which should revolve exactly once a day, once a week, or for any other desired period;

(*b*) *The strip chart.* This chart is driven on rollers past the pen arm, and by altering the chart speed the recorder can operate for periods from one week to a month or even longer. The time scale on this chart can be large enough for the intensity to be calculated with ease.

Instead of recording the information on a strip chart, the value to be recorded may be mechanically or electronically converted to digital form and recorded at uniform time intervals on magnetic tape or as a set of holes punched in paper tape for later automatic reading and processing. Systems incorporating solid-state interrogable memories are also being developed and tested.

The movement of a float, bucket, or weighing mechanism can also be converted into an electric signal and transmitted by radio or wire to a distant receiving station.

7.4 Snowfall

Snowfall is the amount of fresh snow deposited over a specified period (generally 24 hours). Thus snowfall does not include the deposition of drifting or blowing snow. Measurements are made in units both of depth and of water equivalent.

7.4.1 *Depth of snowfall*

Direct measurements of the depth of fresh snow on open ground are made with a graduated ruler or scale. A sufficient number of vertical measurements should be made, in places where drifting is considered absent, to provide a representative average. Special precautions should be taken so as not to measure any previously fallen snow. This can be done by sweeping a suitable patch clear beforehand or by covering the top of the old snow surface with a piece of suitable material (such as wood with a slightly rough surface, painted white) and measuring the depth accumulated on it. On a sloping surface (to be avoided if possible) measurements should still be made with the measuring rod vertical. If there is a layer of old snow, it would be incorrect to calculate the depth of new snow from the difference between two consecutive measurements of total depth of snow since lying snow tends to become compressed and to suffer ablation. Where extensive drifting of snow has occurred, a larger number of measurements are needed to obtain a representative depth.

7.4.2 *Water equivalent of snowfall*

The water equivalent of a snowfall is the equivalent amount of liquid water contained in that snowfall. It may be determined by any of the three methods described hereafter. In the two methods which involve sampling over an area, it is important that sufficient samples be taken to ensure that the mean value has the desired degree of accuracy.

7.4.2.1 *Weighing or melting snow samples*

Cylindrical samples of fresh snow may be taken with a suitable snow sampler and either weighed or melted. Details of the available instruments and sampling techniques are described in 7.8.1.1.3 and 7.8.1.1.4.

7.4.2.2 *Precipitation gauges*

Except for gauges with orifices less than 200 cm^2 in area, all gauges suitable for measuring liquid precipitation can also be used to measure solid precipitation. Where solid precipitation is common and important, a number of special modifications are commonly used to improve the accuracy of measurement. Such modification may be simple as, for example, the removal of the raingauge funnel at the beginning of the snow season or the provision of a special snow cross to protect the catch from blowing out, or they may be complex with the provision of large and elaborate double fences around the gauge to reduce the error caused by deformation of the wind field above the gauge and by drifting of snow into the gauge. Even with such special modifications, the systematic error of measurement of solid precipitation is commonly large and may be up to an order of magnitude greater than those normally associated with measurements of liquid precipitation. Adjustments for this error can in part be attempted by using procedures similar to those referred to in 7.2.4.

Snow collected in non-recording precipitation gauges should be either weighed or melted immediately after each observation and then measured, using a standard graduated measuring cylinder. The only relatively satisfactory recording gauge available for measuring solid precipitation is of the weighing type; float-type gauges are unsatisfactory because the heat released to melt the falling snow accentuates evaporation losses.

The depth of fresh snow is converted to water equivalent, using the appropriate specific density if known. Although the relationship stating that one centimetre of fresh snow equals one millimetre of water equivalent may be used with caution for long-term average values, it may be highly inaccurate for a single measurement as the specific density of snow may vary between 0.03 and 0.4.

7.5 Observations of precipitation using radar

7.5.1 *Limitations*

Radar is able to detect the presence of precipitation up to a range limited principally by the parameters of the system, the size and number of drops per unit volume and the effect of the Earth's curvature. In some circumstances this range can be as great as 400 km, but for practical purposes, particularly in temperate latitudes, it is usually not greater than 250 km. In its simplest form a radar system permits observations of the local movement of areas of precipitation and allows some estimation of the rate of rainfall.

7.5.2 *Extent of coverage*

With the addition of data-processing equipment it is possible, in virtual real time, to estimate rainfall over an area with an accuracy comparable with that of a substantial network of conventional precipitation gauges. The size of the effective catchment area is again limited by the parameters of the radar and also by geographical features. The maximum size is about 3×10^4 km^2, i.e. corresponding to a radius of about 100 km from the radar site. The derived data are of direct value to hydrologists and drainage authorities, as well as to meteorologists. They can also be of value to agriculture, the building industry, aviation, surface transport, and the general public.

7.5.3 *Radar design features*

The design of a precipitation-measuring radar involves a compromise between various parameters, principally wavelength, beamwidth and cost. The choice of wavelength is important since the shorter wavelengths (8 mm, for instance) are subject to attenuation due to hydrometeors and to water vapour absorption. On the other hand, the shorter wavelengths allow a particular beamwidth to be obtained with a smaller antenna. A narrow beam of about 1° is required in order to:

(*a*) Reduce permanent echoes as far as possible;

(*b*) Minimize the enhanced echoes that occur upon intersection with the melting layer; and

(*c*) Resolve small volumes of precipitation.

In these circumstances a 10 cm (S-band) wavelength – an antenna of 8 m diameter – is desirable in tropical zones. For temperate latitudes a 5.6 cm (C-band) wavelength – an antenna of 4 m diameter – is preferred.

7.5.4 *Receiver logarithmic characteristic*

Precipitation rates to be measured vary from almost zero to a few hundred mm h^{-1}. Because of this wide range, to attain the greatest possible accuracy it is essential to have a radar receiver with a logarithmic characteristic, with a dynamic range of about 80 dB and an accuracy at all points within this range of ±1 dB. A minimum detectable signal of about −107 dBm is desirable. The radar transmitter and receiver performance must remain stable; to this end a means of checking the performance should be included in the system. Further, the installation of two or three carefully sited telemetering precipitation gauges within the area in which rainfall is to be measured is necessary in order to calibrate the radar in terms of precipitation intensity at ground level.

7.5.5 *Comparison with raingauge network*

With well-designed processing equipment and accompanying software, it is possible to achieve areal measurements comparable to those obtained with precipitation-gauge networks of, say, one gauge per 50 to 500 km^2, this gauge density depending on the type of rain. Alternatively, it can be said that, even in mountainous areas, accuracies of ±15 per cent in hourly rainfall totals over small sub-catchments are possible under ideal conditions.

7.5.6 *Distant displays*

The processing equipment may also be used to convert the data into suitable form for transmission via conventional telephone or microwave links with either subsequent reconstitution in visual form at a distant point or compositing by computer of data from several radars into an overall picture. The data may also be sorted into sub-catchment totals and transmitted either for direct print-out or display, or for input into another computer for further processing in, for instance, hydrological models.

7.5.7 *Observing snowfall*

Measurement of snowfall by radar is still at a preliminary stage. Preliminary work shows that an accuracy comparable to that in measuring rainfall is achievable with dry snow, but wet snow requires the use of other independent measurements of snow depth at different terrain heights, a technique which cannot yet be considered to have reached operational status.

7.5.8 *Measurement by path attenuation*

It is also possible to measure rate of rainfall by means of the attenuation of electromagnetic waves between two points. This is best done at shorter wavelengths such as 0.86 cm (K-band) where the attenuation coefficient is greater. Work in this area is mainly experimental. Some encouraging results have been obtained with dual-wavelength systems, at 0.86 cm and 3 cm, the former measuring attenuation and the latter reflectivity.

7.5.9 *Storm detection*

Radar is invaluable in the detection of tropical storms and cyclones for which it is essential to use a 10 cm wavelength, as this is attenuated relatively little by comparison with the shorter wavelengths. It is possible, with a well-sited radar, to detect the heavy precipitation associated with such storms and cyclones at ranges exceeding 400 km, particularly if the conditions result in anomalous propagation of the electromagnetic waves. These normally travel on a path of mean radius about four times that of the Earth, which would prevent the detection of any potential target below a height of 9.4 km at a range of 400 km.

7.5.10 *Observing storm development*

The echoes received from severe convective storms are generally recognizable, having a characteristic shape when displayed visually. It is thus possible to track the movement and to monitor build-up and decay of such storms.

7.5.11 *Radial wind components*

Doppler radar is able to measure the radial component of motion of scattering targets. This enables determination of the wind velocity and turbulence within severe storms and assists in tracking. The effective range, however, is considerably less than that of conventional radar. Experimental work aimed toward future operational use of this type of radar is now being carried out.

7.5.12 *Other literature*

Further information on methods of measuring rainfall by radar can be found in WMO Technical Note No. 78, *Use of ground-based radar in meteorology*, and in section 2.1.6 of the WMO *Guide to Hydrological Practices* (WMO – No. 168).

7.6 Observations of precipitation by satellite

Satellites can be used for observation of large and important storm systems. From these observations, useful information as to the probable areal extent and time distribution of precipitation can be inferred.

Rough estimates of rainfall amounts can be made from satellite cloud observations. Such estimates are based on the amount, type and thickness of clouds as observed or inferred, and the probability of rainfall and likely rainfall intensity associated with each cloud type (Collier and Murray, 1972; Follansbee, 1976).

7.7 Measurement of dew, rime and hoar frost

7.7.1 *Measurement of dew*

The deposition of dew is essentially a nocturnal phenomenon and, although relatively small in amount and locally variable, is of much interest in arid zones; in very arid regions it may be of the same order of magnitude as the rainfall.

In order to assess the hydrological contribution of dew, it is necessary to distinguish between dew formed as a result of the downward transport of atmospheric moisture condensed on cooled surfaces, known as "dewfall", and that formed by water vapour evaporated from the soil and plants and condensed on cooled surfaces, known as "distillation dew". Both sources generally contribute simultaneously to the observed dew, although only the former provides additional water to the surface. A further source of moisture results from fog or cloud droplets being collected by leaves and twigs and reaching the ground by dripping or by stem flow. All three forms of precipitation are sometimes referred to as occult precipitation.

The amount of dew deposited on a given surface in a stated period is usually expressed in units of kilograms per m^2 or in millimetres depth of dew. Whenever possible the amount should be measured to the nearest tenth of a millimetre. The amount of dew depends, however, very much on the properties (including size) of the surface, and the results obtained instrumentally are not necessarily representative of the deposit of dew on natural objects.

Empirical relationships between instrumental measurements and the deposition of dew on a natural surface should therefore be established for each particular set of conditions of surface and exposure.

7.7.1.1 *Methods of measurement*

The most direct method is by exposing at sunset a dried, weighed plate of hydroscopic material, such as gypsum, plant tissue or blotting paper and reweighing it after sunrise, the increase in weight being assumed to be caused by dew. This method is inconvenient for routine observations because of the need to bring the plate inside or protect it at sunrise to prevent evaporation and also because very accurate weighing is necessary. Moreover, the effect of any rain or other precipitation has to be allowed for.

A number of instruments for the direct measurement of the occurrence, amount and duration of dew have been developed. Dew-duration recorders use either elements which themselves change in such a manner as to indicate or record the wetness period, or electrical sensors in which the electrical conductivity of the surface of natural or artificial leaves changes in the presence of water due to rain, snow, wet fog or dew. In dew balances, the amount of moisture deposited in the form of precipitation or dew is weighed and recorded. In most weighing instruments providing a continuous trace, it is possible to distinguish between moisture deposits caused by fog, dew or rain by consideration of the type of trace.

Considerable effort has been devoted, but without much success, to devising means of measuring leaf wetness from artificial surfaces in the hope of yielding results comparable to those for natural conditions. A review of the instruments designed for measuring duration of leaf wetness and an assessment of the extent to which various instruments give readings representative of plant surface wetness is published as an appendix to WMO Technical Note No. 55 – *The influence of weather conditions on the occurrence of apple scab*. These devices can only be used as a qualitative guide in any particular situation or as a crude means of regional comparison, careful interpretation being required in either role. Unless the collecting surface is more or less flush with the natural surface and of very similar properties it will not correctly indicate the amount of dew deposited on the natural surface of interest.

Micrometeorological measurements have been used to calculate average dewfall over an area, but the precision of the measurements required and the lack of knowledge of transfer coefficients under very stable conditions make the method unsuitable for routine practice. The only certain method of measuring net dewfall by itself is by the use of a sensitive lysimeter. However, this method does not record distillation dew, since no change in weight would accompany distillation dew. The only generally accepted means of measuring the total amount of dew is by the blotting technique, that is by weighing a number of filter papers both before and after they are thoroughly pressed against the surface of interest.

7.7.2 *Observation of ice accumulation*

Observations of rime and hoar frost include both the measurement of the dimensions and weight of the ice deposit and a visual description of their appearance. A system consisting of rods and stakes with two pairs of parallel wires, one pair oriented north-south and the other east-west, can be used to accumulate ice. The wires may be suspended at any level, and the upper wire of each pair should be removable. At the time of observation, both upper wires are removed, placed in a special container and taken indoors for melting and weighing of the deposit. The cross-section of the deposit is measured on the permanently fixed lower wires.

Recording instruments are used in some countries for continuous registration of rime. A vertical or horizontal rod, ring or plate is used as the sensor and the increase in the amount of rime with time is recorded on a chart. A simple device called an ice-scope is used to determine the appearance and presence of rime and hoar frost on a snow surface. The ice-scope consists of a round plywood disk, 30 cm in diameter, which can be moved up or down and set at any height on a vertical rod fixed in the ground. Normally the disk is set flush with the snow surface to collect the rime and hoar frost. Rime is also collected on a 20 cm diameter ring fixed on the rod, 20 cm from its upper end. A wire or thread 0.2-0.3 mm in diameter, stretched between the ring and the top end of the rod, is used for the observation of rime deposits. If necessary, each sensor can be removed and weighed.

Observations of ice accumulation are most important in mountain areas where such accumulation on the windward side of a mountain may exceed the "normal" precipitation.

7.8 Snow-cover measurement

The snow that accumulates in a drainage basin is a natural storage reservoir, which in some areas forms a major source of the annual water supply. Forecasts of this water supply are of importance to farmers, ranchers, shippers and bankers, and to agencies concerned with power production, water supplies and flood control. Reliable predictions of the seasonal runoff from a drainage basin owing to snowmelt can be made after several years of observation on the basis of the correlation between the weighted water equivalent of the snow cover at snow courses (see 7.8.1.1), at the time of maximum accumulation or as appropriate, and the runoff as measured at a gauging station.

7.8.1 *Water equivalent of snow cover*

The water equivalent of a snow cover is the vertical depth of the water layer that would be obtained by melting the snow cover.

7.8.1.1 *Snow courses*

A snow course is defined as a permanently marked area where snow surveys are taken each year.

7.8.1.1.1 *Selection of snow courses*

Snow courses should be carefully selected, so that measurements of the water equivalent will from year to year provide a reliable index of the water in snow storage over the entire basin. For conceptual hydrological modelling, the snow-course water equivalents should be as close as possible to the average actual water equivalent of the snow cover over the basin, so they are useful indices for application in regression-type water-yield forecasts. Good locations for snow courses in mountainous areas are characterized by:

(*a*) Enough protection from the wind to minimize the effects of redistribution by the wind;

(*b*) Elevations and exposures where there is little or no melting prior to the peak accumulation, if the total seasonal accumulation is to be measured;

(*c*) Sites which are sufficiently accessible to ensure continuity of surveys.

In flat terrain, the snow course should be so located that the average water equivalent determined there will represent as nearly as possible the actual average water equivalent of the snow stored in the area.

7.8.1.1.2 *Points of measurement*

Measurement along a snow course in mountainous terrain usually consists of taking samples at points spaced 20 to 40 m apart. More samples will be required in large open areas where snow will tend to drift owing to wind action. Since sufficient knowledge of the tendency of the snow to drift is initially lacking, it is expedient to make an extensive survey having long traverses and a large number of measurements. Once the prevailing length and direction of the snowdrifts have been ascertained, it may be possible to reduce the number of measurement points.

In flat terrain, the distance between points of snow sampling for density should be 100 to 500 m, depending upon local conditions. Depth of snow along the snow course should also be measured at about five equally spaced points between sampling points.

Each sampling point should be located by measuring its distance from a reference point as marked on a map of the snow course. Stakes set high enough to extend above the deepest snow and offset from the course far enough not to affect the snow cover may be placed as reference point markers opposite each point where snow samples are to be taken, or at as many reference points as necessary to minimize possible errors in locating the sampling point. The ground surface should be cleared of rocks, stumps, and brush for two metres in all directions from each point selected for sampling, and watercourses and irregular ground surfaces should be avoided by at least that distance. If a course meanders through timber and if small openings are used as places for sampling, each point may be located with respect to two or three marked trees.

7.8.1.1.3 *Snow-sampling equipment*

Snow-sampling equipment commonly consists of a metal or plastic tube with a snow cutter fixed at its lower end and with a scale stamped on its exterior surface throughout its length; a spring or lever balance for determining the weight of the snow cores; a wire cradle for supporting the tube while it is being weighed; and tools for operating the snow sampler.

The cutter should be designed to penetrate various types of snow and through crusted and icy layers, while not compacting the snow. The shape of the cutter and the shape and number of teeth should allow for efficient removal of ice chips outside the core, while also enabling the core to be retained when the sample is withdrawn.

The sampling tube should allow full upward passage of the core within it. Some tubes are slotted to provide visual evidence that the core length is similar to the snow depth and to allow for easier cleaning of the tube after the sample has been removed.

The spring balance is the most practical weighing apparatus as it may be easily set up and read, even under windy conditions. Although lever balances are potentially more accurate, they are very difficult to use, especially in wind, so that the greater accuracy is seldom realized.

Another procedure is to store the samples in plastic containers or bags and return them to a base station where they may be accurately weighed, or melted and measured with a graduate. In practice this procedure is not easily carried out as the samples must 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 taken at once. The results may be noted down on-site with other pertinent observations; if a good notebook is kept there can be little chance of confusion as to location or conditions.

In all measurements of this type extremely difficult physical conditions under which observations must frequently be made should always be kept in mind and practical considerations should prevail in sampler designs. Further details are given in the WMO *Guide to Hydrological Practices*.

7.8.1.1.4 *Snow-sampling procedure*

Sampling-point locations should be determined with an accuracy of 5 m by measuring from a reference mark, as indicated on the map of the snow course.

To cut the core, the sampler – cutter end first – is forced vertically downward through the snow cover until it reaches the ground. If snow conditions permit, a steady downward thrust intended to effect the uninterrupted flow of the core into the tube is best. A minimum amount of turning in a right-hand direction is possible without interrupting the downward thrust; this brings the cutter into play, which is desirable for quick penetration of thin ice layers.

To prevent loss of the core through the cutter end while the sampler is being withdrawn from the snow, sufficient soil should be gathered in the cutter to serve as a plug. To what extent this will have to be done depends on the condition of the snow. For example, two or three centimetres of solid soil may be required to hold slush. A trace of ground litter on the lower end of the sampler is an indication that no loss has occurred.

With the cutter at or slightly below ground level and the sampler standing vertically, the reading on the scale that corresponds to the top of the snow is observed. When the depth the sampler has penetrated beyond the bottom of the snow cover is ascertained and deducted from this reading, the result is recorded. This is an important reading, since it is used in computing the snow density.

The length of snow core obtained may be observed through the tube slots and read on the scale on the outside of the samples. After this reading has been corrected for any foreign matter picked up in the cutter end, it is recorded. The sole purpose of this reading is to provide a means for quickly judging whether a complete sample of the snow cover has been procured. The length of a true core cannot be expressed as a fixed ratio of the snow depth for all conditions of snow, but the relation of snow-core length to snow depth will remain fairly constant on an individual course at a particular time.

The measurement is completed by carefully weighing the snow core in the tube. The weight of the snow core in equivalent centimetres of water can be read directly on the scale of the balance. The density of the snow is computed by dividing the water equivalent of the snow by the depth of the snow. The density should be reasonably constant over the entire course. A large deviation from the average usually indicates an error in the measurement at an individual point.

7.8.1.1.5 *Accuracy of measurements*

The accuracy of measurements of depth (H) or of the water equivalent depth (W) of snow cover, at separate points of the snow course, employing the most widely used instruments (VS-43, N-78 snow samplers (U.S.S.R.), Mount Rose sampler (U.S.A.) and other similar instruments) depends on the graduations of the scales in question and on instrumental and subjective random errors.

A decrease of the random errors for H or W can be achieved by calculating the mean of measurements at separate points. The necessary number of measurements to ensure that the desired relative accuracy of mean values is attained for a given division of the scale of an instrument can be determined as shown by Konovalov (1973).

7.8.2 **Depth and extent of snow cover**

Measurements of snow cover over extended areas together with an established local correlation with density make possible an approximation of its water equivalent.

7.8.2.1 *Measurement with graduated snow stakes*

The most common method for determining the depth of snow cover, primarily in regions of deep snow, is by means of a calibrated stake fixed at a representative site which can easily be inspected from a distance. This procedure may be acceptable if the representativeness of the site is proven and the immediate surroundings of the site (about 10 m in radius) are protected against trespassing by very loose wire fences which do not adversely influence the site. The readings are taken by sighting over the undisturbed snow surface.

The stakes should be painted white to minimize undue melting of snow immediately surrounding them. The entire length of the stake should be graduated in metres and centimetres. In inaccessible areas, stakes are provided with crossbars so that they can be read from a distance with the aid of field glasses, telescopes or aircraft.

In the case of measurements of snow depth from aircraft, visual readings by snow stakes may be supplemented by large-scale photographing of the stakes.

7.8.2.2 *Measurement with a snow tube*

The vertical depth of snow cover may also be measured by direct observation with a graduated snow tube, usually during the course of obtaining the water equivalent, as described in 7.8.1.1.4.

7.8.2.3 *Measurement by photogrammetric methods*

7.8.2.3.1 *Aerial photography*

Aerial photography can be used to provide data on the maximum depth and the extent of snow cover in barren and sparsely wooded mountainous basins. For these purposes, aerial photographs of the basin should be obtained before the snow season and again at about the time of maximum snow accumulation. Horizontal and vertical control stations for the photography are identified by tall poles so that the same points can be easily relocated on photographs of the snow cover. Snow depth is determined by subtracting photogrammetrically determined ground-surface elevations from similarly determined snow-surface elevations at sample points. Thus, an average depth of snow cover on the basin can be estimated. The accuracy of the determination of the depth of the snow cover by this method depends on the scale of the photographs and the accuracy of the horizontal and vertical control for the photography. A useful scale for aerial photography for this purpose is 1:6000. For a deep snow cover and favourable photographic conditions, the accuracy may be within ± 10 per cent of the depth of snow cover. Aerial photogrammetry is fairly costly but its principal value is providing information about the quantity and distribution of snow cover that cannot readily be obtained in any other way.

7.8.2.3.2 *Terrestrial photography*

The elevation of the snow line on mountain slopes may be determined also by means of photo-theodolite photography (terrestrial photogrammetry). The theodolite is positioned periodically at predetermined 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 that of aerial photogrammetry.

7.8.2.3.3 *Satellite photography*

Satellite photographs obtained for cloud cover observations can also be used to give a general determination of the extent of snow cover, in both mountainous and level terrain. The methods of processing and utilizing such information are dealt with in detail in the WMO *Guide to Hydrological Practices.*

7.8.3 ***Radio-isotopic snow measurement***

Radioactive gamma sources are used in various ways to measure water equivalent of snow. Attenuation of gamma radiation may be used to estimate the water equivalent of a snow cover between a source and a detector. One type of installation (vertical) is used to measure total water equivalent above or below a point source. A second installation (horizontal) measures water equivalent between two vertical tubes at selected distances above the ground. However, such apparatus is complex and expensive, and special precautions appropriate to the use of radioactive materials must be taken.

A high-energy source and a suitable detector are placed so that the snow layer lies between them; the particular arrangement determines whether a horizontal or vertical profile or both are obtained.

7.8.4 ***Snow pillows***

Snow pillows of various dimensions and materials are used to measure the weight of snow that accumulates on the pillows. The most common pillows are flat circular containers (diameter 3.7 m) of rubberized material filled with a non-freezing liquid. The pillow is installed on the surface of the ground, flush with the ground or buried under a thin layer of soil or sand. In order to prevent damage to the equipment and to preserve the snow cover in its natural condition, it is recommended that the site be fenced in. Under normal conditions, snow pillows can be used for ten years or more.

Hydrostatic pressure inside the pillow is a measure of the weight of the snow on the pillow. Measurement of the hydrostatic pressure by means of a float-operated liquid-level recorder or a pressure transducer provides a method of continuous measurement of the water equivalent of the snow cover. Variations in accuracy of measurements may be induced by temperature changes. Temperature effects may be reduced by installing the access tube to the measurement section in a temperature-controlled shelter or by having the access tube and measurement unit in the ground.

The results of measurements of the water equivalent of snow by snow pillows, as well as charts of self-recording instruments, may also be transmitted on the telecommunication channels.

Snow pillow measurements differ from those made with standard snow tubes, especially during the snowmelt period. They are most reliable when the snow cover does not contain ice layers, which can cause "bridging" above the pillows.

A comparison of the water equivalent of snow determined by snow pillow, with measurements by the standard method of weighing, has indicated that these may differ by five to ten per cent.

7.8.5 *Natural gamma radiation*

The method of gamma-radiation snow surveying is based on attenuation by snow of gamma radiation emanating from natural radioactive elements in the top layer of the soil. The greater the water equivalent of the snow, the more the radiation is attenuated. The ratio of gamma radiation intensity measured above the snow cover to that measured over the same course before snow accumulation provides an estimate of the water equivalent.

An aerial survey provides integrated areal estimates of snow-cover water equivalents, which are suitable for mapping. The usual flying height for making such a survey is 25-100 m.

Measurements consist of total count for a large energy range and spectral counts for specific energy levels. The spectral information permits correction for spurious radiation induced by cosmic rays and radioactivity of the atmosphere.

The accuracy of an aerial gamma survey of snow cover depends primarily on the precision of the radiation-measuring equipment, fluctuations in the cosmic radiation and in the radioactivity in the layer of the atmosphere near the ground, soil-moisture variation in the top 15 cm, uniformity of snow distribution, absence of extensive thawing, and steady flying conditions for successive flights. The expected error ranges between ± 10 per cent, with a lower limit of approximately 1 cm water equivalent. Further details for the aerial survey, for ground surveys and for methods using cosmic radiation are given in the Gidrometeoizdat Manual (1971).

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