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CHAPTER 6. MEASUREMENT OF PRECIPITATION**6.1 GENERAL**

This chapter describes the well-known methods of precipitation measurements at ground stations.

It also addresses precipitation intensity measurements (in particular the rate of rainfall or rainfall intensity) due to the rapidly increasing need for such measurements for the interpretation of rainfall patterns, rainfall event modelling and forecasts.

This chapter does include measurement of precipitation in the form of snow precipitation and other solid precipitation, while measurement of snow on the ground and new snow are discussed in detail in Volume II, Chapter 2. This chapter does not discuss measurements which attempt to define the structure and character of precipitation, or which require specialized instrumentation, which are not standard meteorological observations (such as drop size distribution). Marine and radar measurements are discussed in Volume III, Chapters 4 and 7 respectively, while space-based observations are discussed in Volume IV.

The general problem of representativeness is particularly acute in the measurement of precipitation. Precipitation measurements are particularly sensitive to exposure, wind and topography, and metadata describing the circumstances of the measurements are particularly important for users of the data.

The analysis of precipitation data is much easier and more reliable if the same gauges and siting criteria are used throughout the networks. This should be a major consideration in designing networks.

6.1.1 Definitions

Precipitation is defined as the liquid or solid products of the condensation of water vapour falling from clouds, in the form of rain, drizzle, snow, snow grains, snow pellets, hail, ice pellets or falling from clear air, in the form of diamond dust.

Moisture can also be transferred to the ground through dew, rime, hoar frost, or fog, but these forms of deposited particles are not included in the definition of precipitation. Nevertheless, they are described in 6.6.

The total amount of precipitation which reaches the ground in a stated period is expressed in terms of the vertical depth of water (or water equivalent in the case of solid forms) to which it would cover a horizontal projection of the Earth's surface.

Precipitation intensity is defined as the amount of precipitation collected per unit time interval. According to this definition, precipitation intensity data can be derived from the measurement of precipitation amount using an ordinary precipitation gauge. In that sense, precipitation intensity is a secondary parameter, derived from the primary parameter precipitation amount. However, precipitation intensity can also be measured directly (see 6.1.4.1).

6.1.2 Units and scales

The unit of precipitation is linear depth, usually in millimetres (volume/area), or kg m^{-2} (mass/area) for liquid precipitation. 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 taken at fixed times common to the entire network or networks of interest. Less than 0.1 mm (or 0.2 mm depending on the resolution used) is generally referred to as a trace.

The measurement unit of rainfall intensity is linear depth per hour, usually in millimetres per hour (mm h^{-1}). Rainfall intensity is normally measured or derived over one-minute time intervals due to the high variability of intensity from minute to minute.

6.1.3 Meteorological and hydrological requirements

Volume I, Chapter 1, Annex 1.A gives a broad statement of the requirements for uncertainty, range and resolution for precipitation measurements.

The common observation times are hourly, three-hourly and daily, for synoptic, climatological and hydrological purposes. For some purposes, such as the design and management of urban drainage systems, forecasting and mitigation of flash floods, transport safety measures, and in general most of the applications where rainfall data are sought in real time, a much greater time resolution is required to measure very high rainfall rates over very short periods (typically 1 min for rainfall intensity). For some other applications, storage gauges are used with observation intervals of weeks or months or even a year in mountains and deserts.

6.1.4 Measurement methods

6.1.4.1 Instruments

Precipitation gauges (or raingauges if only liquid precipitation can be measured) 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, with a funnel if its main purpose is to measure rain. Since various sizes and shapes of orifice and gauge heights are used in different countries, the measurements are not strictly comparable (WMO, 1989a). The volume or weight of the catch is measured, the latter in particular for solid precipitation. The gauge orifice may be at one of many specified heights above the ground or at the same level as the surrounding ground. The orifice must be placed above the maximum expected depth of snow cover, and above the height of significant potential in-splashing from the ground. For solid precipitation measurement, the orifice is above the ground and an artificial shield should be placed around it. The most commonly used elevation height in more than 100 countries varies between 0.5 and 1.5 m (WMO, 1989a).

The measurement of precipitation is very sensitive to exposure, and in particular to wind. Section 6.2 discusses exposure, while section 6.4 discusses at some length the errors to which precipitation gauges are prone, and the corrections that may be applied.

Rainfall intensity can be either derived from the measurement of precipitation amount using a recording raingauge (see 6.5) or measured directly. The latter can be done, for example, by using a gauge and measuring the flow of the captured water, measuring the accretion of collected water as a function of time, or using some optical principles of measurement. A number of techniques for determining precipitation amount are based on these direct intensity measurements by integrating the measured intensity over a certain time interval.

This chapter also refers to some other special techniques for measuring solid precipitation, and other types of precipitation (dew, and the like). Some techniques which are in operational use are not described here, for example, the optical raingauge, which makes use of optical scattering. Useful sources of information on new methods under development are the reports of recurrent

conferences, such as the Technical Conference on Meteorological and Environmental Instruments and Methods of Observation (TECO), the international workshops on precipitation measurement (for example, Slovak Hydrometeorological Institute and Swiss Federal Institute of Technology, 1993; WMO, 1989b), and the instrument intercomparisons organized by the Commission for Instruments and Methods of Observation (for example, WMO, 1998).

Point measurements of precipitation serve as the primary source of data for areal analysis. However, even the best measurement of precipitation at one point is only representative of a limited area, the size of which is a function of the length of the accumulation period, the physiographic homogeneity of the region, local topography and the precipitation-producing process. Radar and satellites are used to define and quantify the spatial distribution of precipitation. In principle, a suitable integration of all three sources of areal precipitation data into national precipitation networks (automatic gauges, radar, and satellite) can be expected to provide sufficiently accurate areal precipitation estimates on an operational basis for a wide range of precipitation data users.

Instruments that detect and identify precipitation, as distinct from measuring it, may be used as present weather sensors, and are referred to in Volume I, Chapter 14.

6.1.4.2 Reference gauges and intercomparisons

Several types of gauges have been used as reference gauges. The main feature of their design is that of reducing or controlling the effect of wind on the catch, which is the main reason for the different behaviours of gauges. They are chosen also to reduce the other errors discussed in 6.4.

Ground-level gauges are used as reference gauges for liquid precipitation measurement. Because of the near absence of wind-induced error, they generally show more precipitation than any elevated gauge (WMO, 1984, 2009). The gauge is placed in a pit with the gauge rim at ground level, sufficiently distant from the nearest edge of the pit to avoid in-splashing. 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. A description and drawings of a standard pit gauge are given in Annex 6.A and more details are provided in WMO (2009) and the EN 13798:2010 standard (CEN, 2010).

The reference gauge for solid precipitation is the gauge known as the Double Fence Intercomparison Reference. It has octagonal vertical double fences surrounding a Tretyakov gauge, which itself has a particular form of wind-deflecting shield. Drawings and a description are given by Goodison et al. (1989) and in WMO (1985, 1998).

Recommendations for comparisons of precipitation gauges against the reference gauges are given in Annex 6.B.

6.1.4.3 Documentation

The measurement of precipitation is particularly sensitive to gauge exposure, so metadata about the measurements must be recorded meticulously to compile a comprehensive station history, in order to be available for climate and other studies and quality assurance.

Section 6.2 discusses the site information that must be kept, namely detailed site descriptions, including vertical angles to significant obstacles around the gauge, gauge configuration, height of the gauge orifice above ground and height of the wind speed measuring instrument above ground.

Changes in observational techniques for precipitation, mainly the use of a different type of precipitation gauge and a change of gauge site or installation height, can cause temporal inhomogeneities in precipitation time series (see Volume V, Chapter 2). The use of differing types of gauges and site exposures causes spatial inhomogeneities. This is due to the systematic errors of precipitation measurement, mainly the wind-induced error. Since adjustment techniques based on statistics can remove the inhomogeneities relative to the measurements of surrounding gauges,

the correction of precipitation measurements for the wind-induced error can reduce the bias of measured values.

The following sections (especially 6.4) on the various instrument types discuss the corrections that may be applied to precipitation measurements. Such corrections have uncertainties, and the original records and the correction formulae should be kept.

Any changes in the observation methods should also be documented.

6.2 SITING AND EXPOSURE

All methods for measuring precipitation should aim to obtain a sample that is representative of the true amount falling over the area which the measurement is intended to represent, whether on the synoptic scale, mesoscale or microscale. The choice of site, as well as the systematic measurement error, is, therefore, important. For a discussion of the effects of the site, see Sevruk and Zahlavova (1994).

The location of precipitation stations within the area of interest is important, because the number and locations of the gauge sites determine how well the measurements represent the actual amount of precipitation falling in the area. Areal representativeness is discussed at length in WMO (1992a), for rain and snow. WMO (2008) gives an introduction to the literature on the calculation of areal precipitation and corrections for topography.

The effects on the wind field of the immediate surroundings of the site can give rise to local excesses and deficiencies in precipitation. In general, objects should not be closer to the gauge than a distance of twice their height above the gauge orifice. For each site, the average vertical angle of obstacles should be estimated, and a site plan should be made. Sites on a slope or the roof of a building should be avoided. Sites selected for measuring snowfall and/or snow cover should be in areas sheltered as much as possible from the wind. 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.

Preferably, however, the effects of the wind, and of the site on the wind, 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 (listed in order of decreasing effectiveness):

- (a) In areas with 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 simulating the effect in (a) through the use of appropriate fence structures;
- (c) By using windshields around the gauge.

The surface surrounding the precipitation gauge can be covered with short grass, gravel or shingle, but hard, flat surfaces, such as concrete, should be avoided to prevent excessive in-splashing.

A classification of measurement sites has been developed in order to quantify and document the influence of the surrounding environment (see Volume I, Chapter 1, Annex 1.D). This classification uses a relatively simple description of the (land-based) sites.

6.3 NON-RECORDING PRECIPITATION GAUGES

6.3.1 Ordinary gauges

6.3.1.1 Instruments

The commonly used precipitation gauge consists of a collector placed above a funnel leading into a container where the accumulated water and melted snow are stored between observation times. Different gauge shapes are in use worldwide as shown in Figure 6.1. Where solid precipitation is common and substantial, a number of special modifications are used to improve the accuracy of measurements. Such modifications include the removal of the raingauge funnel at the beginning of the snow season or the provision of a special snow fence (see WMO, 1998) to protect the catch from blowing out. Windshields around the gauge reduce the error caused by deformation of the wind field above the gauge and by snow drifting into the gauge. They are advisable for rain and essential for snow. A wide variety of gauges are in use (see WMO, 1989a).

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Figure 6.1. Different shapes of standard precipitation gauges. The solid lines show streamlines and the dashed lines show the trajectories of precipitation particles. The first gauge shows the largest wind field deformation above the gauge orifice, and the last gauge the smallest. Consequently, the wind-induced error for the first gauge is larger than for the last gauge.

Source: Sevruk and Nespor (1994)

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The stored water is either collected in a measure or poured from the container into a measure, or its level in the container is measured directly with a graduated stick. The size of the collector orifice is not critical for liquid precipitation, but an area of at least 200 cm² is required if solid forms of precipitation are expected in significant quantity. An area of 200 to 500 cm² will probably be found most convenient. 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 on the inside, and be steeply bevelled on the outside; the design of gauges used for measuring snow should be such that any narrowing of the orifice caused by accumulated wet snow about the rim is small;
- (b) The area of the orifice should be known to the nearest 0.5 %, 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 achieved if the vertical wall is sufficiently deep and the slope of the funnel is sufficiently steep (at least 45 %). Suitable arrangements are shown in Figure 6.2;
- (d) The construction should be such as to minimize wetting errors. This can be done by choosing the proper material and minimizing the total inner surface of the collector;
- (e) The container should have a narrow entrance and be sufficiently protected from radiation to minimize the loss of water by evaporation. Precipitation gauges used 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.

The measuring cylinder should be made of clear glass or plastic which has a suitable coefficient of thermal expansion and should be clearly marked to show the size or type of gauge with which it is to be used. Its diameter should be less than 33 % 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 another suitable material that 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. When this is the case, rods made 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 include an allowance for the displacement caused by 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.

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Figure 6.2. Suitable collectors for raingauges

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6.3.1.2 Operation

The measuring cylinder must be kept vertical when it is being read, and the observer must be aware of parallax errors. 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. It is also possible to measure precipitation catch by accurate weighing, a procedure which has several advantages. The total weight of the can and contents is measured and the known weight of the can is subtracted. There is little likelihood of spilling the water and any water adhering to the can is included in the weight. The commonly used methods are, however, simpler and cheaper.

6.3.1.3 Calibration and maintenance

The graduation of the measuring cylinder or stick must, of course, be consistent with the chosen size of the collector. The calibration of the gauge, therefore, includes checking the diameter of the gauge orifice and ensuring that it is within allowable tolerances. It also includes volumetric checks of the measuring cylinder or stick.

Routine maintenance should include, at all times, keeping the gauge level in order to prevent an out-of-level gauge (see Rinehart, 1983; Sevruk, 1984). As required, the outer container of the gauge and the graduate should be kept clean at all times both inside and outside by using a long-handled brush, soapy water and a clean water rinse. Worn, damaged or broken parts should be

replaced, as required. The vegetation around the gauge should be kept trimmed to 5 cm (where applicable). The exposure should be checked and recorded.

6.3.2 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 that is large enough to store the seasonal catch (or the monthly catch in wet areas). A layer of no less than 5 mm of a suitable oil or other evaporation suppressant should be placed in the container to reduce evaporation (WMO, 1972). This layer should allow the free passage of precipitation into the solution below it.

An antifreeze solution may be placed in the container to convert any snow which falls into the gauge into a liquid state. It is important that the antifreeze solution remain dispersed. A mixture of 37.5 % by weight of commercial calcium chloride (78 % purity) and 62.5 % water makes a satisfactory antifreeze solution. Alternatively, aqueous solutions of ethylene glycol or of 1,2-Propylen glycol are used. Not recommended are antifreezes with dangerous properties (hazardous good for transport or hazardous material while handling) especially containing methanol, a dangerous material classified (high) toxic. Thorough reading of Safety Data Sheet (SDS), also called Material Safety Data Sheet (MSDS) is highly recommended. This compulsory document provided by the manufacturer for each chemicals or salt details all relevant information on the composition, properties, potential danger, safety measures, handling and storage of the said chemicals.

While more expensive, the latter solutions are less corrosive than calcium chloride and give antifreeze 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 % of the total volume of the gauge.

In some countries, this antifreeze and oil solution is considered toxic waste and, therefore, harmful to the environment. Guidelines for the disposal of toxic substances should be obtained from local environmental protection authorities.

The seasonal precipitation catch is determined by weighing or measuring the volume of the contents of the container (as with ordinary gauges; see 6.3.1). The amount of oil and antifreeze 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. Corrections may be applied as with ordinary gauges.

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

6.4 PRECIPITATION GAUGE ERRORS AND CORRECTIONS

It is convenient to discuss at this point the errors and corrections that apply in some degree to most precipitation gauges, whether they are recording or non-recording gauges. The particular cases of recording gauges are discussed in 6.5.

Comprehensive accounts of errors and corrections can be found in WMO (1982, 1984, 1986; specifically for snow, 1998; and specifically for rainfall intensity, 2006, 2009). Details of the models used for adjusting raw precipitation data in Canada, Denmark, Finland, the Russian Federation, Switzerland and the United States are given in WMO (1982). WMO (1989a) gives a description of how the errors occur. There are collected conference papers on the topic in WMO (1986, 1989b). Details on the improvement of the reliability of rainfall intensity measurements as

obtained by traditional tipping-bucket gauges, weighing gauges and other types of gauges (optical, floating/siphoning, etc.) are given in WMO (2006, 2009).

The amount of precipitation measured by commonly used gauges may be less than the actual precipitation reaching the ground by up to 30 % or more. Systematic losses will vary by type of precipitation (snow, mixed snow and rain, and rain). The systematic error of solid precipitation measurements is commonly large and may be of an order of magnitude greater than that normally associated with liquid precipitation measurements.

For many hydrological purposes it is necessary first to make adjustments to the data in order to allow for the error before making the calculations. The adjustments cannot, of course, be exact (and may even increase the error). Thus, the original data should always be kept as the basic archives both to maintain continuity and to serve as the best base for future improved adjustments if, and when, they become possible.

The traditional assessment of errors in precipitation gauges refers to so-called weather-related errors. It is well recognized that the measurement of liquid precipitation at the ground is affected by different sources of systematic and random errors, mainly due to wind-, wetting- and evaporation-induced losses (see WMO, 1982) which make the measurement of light to moderate rainfall scarcely reliable in the absence of an accurate calibration. Wind-induced errors still have an influence on rainfall intensities of the order of 20–50 mm h⁻¹ with an incidence of about 5 % observed in some intercomparison stations in central Europe (WMO, 1984). Sampling errors due to the discrete nature of the rain measurement are also recognized to be dependent on the bucket size (for tipping-bucket gauges) and sampling interval or instrument response time, though not on precipitation intensity, and can be analytically evaluated (Colli et al., 2013a).

The true amount of precipitation may 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: typically 2 % to 10 % for rain and 10 % to 50 % for snow;
- (b) Error due to the wetting loss on the internal walls of the collector;
- (c) Error due to the wetting loss in the container when it is emptied: typically 2 % to 15 % in summer and 1 % to 8 % in winter, for (b) and (c) together;
- (d) Error due to evaporation from the container (most important in hot climates): 0 % to 4 %;
- (e) Error due to blowing and drifting snow;
- (f) Error due to the in- and out-splashing of water: 1 % to 2 %;
- (g) Systematic mechanical and sampling errors, and dynamic effects errors (i.e. systematic delay due to instrument response time): typically 5 % to 15 % for rainfall intensity, or even more in high-rate events (see WMO, 2009);
- (h) Random observational and instrumental errors, including incorrect gauge reading times.

The first seven error components are systematic and are listed in order of general importance. The net error due to blowing and drifting snow and to in- and out-splashing of water can be either negative or positive, while net systematic errors due to the wind field and other factors are negative. Since the errors listed as (e) and (f) above are generally difficult to quantify, the general model for adjusting data from most gauges, originally proposed by WMO (1982) and later modified by Legates and Willmott (1990), can be written as:

$$P_k = k_r P_{cr} + k_s P_{cs} = k_r (P_{gr} + \Delta P_{1r} + \Delta P_{2r} + \Delta P_{3r} + \Delta P_{4r}) + k_s (P_{gs} + \Delta P_{1s} + \Delta P_{2s} + \Delta P_{3s} + \Delta P_{4s}) \quad (6.1)$$

where subscripts r and s refer to liquid (rain) and solid (snow) precipitation, respectively; P_k is the adjusted precipitation amount; k (see Figure 6.3) is the adjustment factor for the effects of wind field deformation; P_c is the amount of precipitation caught by the gauge collector; P_g is the measured amount of precipitation in the gauge; ΔP_1 is the adjustment for the wetting loss on the internal walls of the collector; ΔP_2 is the adjustment for wetting loss in the container after emptying; ΔP_3 is the adjustment for evaporation from the container; and ΔP_4 is the adjustment for systematic mechanical errors.

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Figure 6.3. Conversion factor k defined as the ratio of "correct" to measured precipitation for rain (top) and snow (bottom) for two unshielded gauges in dependency of wind speed u_{hp} , intensity i and type of weather situation according to Nespor and Sevruk (1999). On the left is the German Hellmann manual standard gauge, and on the right the recording, tipping-bucket gauge by Lambrecht. Void symbols in the top diagrams refer to orographic rain, and black ones to showers. Note the different scales for rain and snow. For shielded gauges, k can be reduced to 50% and 70% for snow and mixed precipitation, respectively (WMO, 1998). The heat losses are not considered in the diagrams (in Switzerland they vary with altitude between 10% and 50% of the measured values of fresh snow).

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Errors due to the weather conditions at the collector, as well as those related to wetting, splashing and evaporation, are typically referred to as catching errors. They indicate the ability of the instrument to collect the exact amount of water according to the definition of precipitation at the ground, that is, the total water falling over the projection of the collector's area over the ground. Systematic mechanical and sampling errors, typically referred to as quantification errors, are related to the ability of the instrument to sense correctly the amount of water collected by the instrument. The WMO laboratory and field intercomparisons on rainfall intensity gauges (WMO 2006, 2009) both contributed to the assessment of quantification errors and documented laboratory and field calibration methods for identifying and/or correcting quantification errors in rainfall intensity measurements. Obviously, these errors may derive from very different aspects of the sensing phase since the instruments may differ in the measuring principle applied, construction details, operational solutions and so forth.

The corrections of precipitation measurement errors are applied to daily or monthly totals or, in some practices, to individual precipitation events.

When dealing with precipitation intensity measurements, systematic mechanical errors can be properly corrected through a standardized laboratory calibration referred to as a dynamic calibration in steady-state conditions of the reference flow rate (Niemczynowicz, 1986; WMO, 2009). For more details, see Annex 6.C.

In general, the supplementary data needed to make adjustments related to weather conditions include the wind speed at the gauge orifice during precipitation, drop size, precipitation intensity, air temperature and humidity, and the characteristics of the gauge site. Although temperature has some effect on gauge undercatch, the effect is significantly less than the effects of wind speed at gauge height (Yang et al., 1993; Yang et al., 1995). Wind speed and precipitation type or intensity may be sufficient variables to determine the corrections. Wind speed alone is sometimes used. At sites where such observations are not made, interpolation between the observations made at

adjacent sites may be used for making such adjustments, but with caution, and for monthly rainfall data only.

For most precipitation gauges, wind speed is the most important environmental factor contributing to the under-measurement of solid precipitation. These data must be derived from standard meteorological observations at the site in order to provide daily adjustments. In particular, if wind speed is not measured at gauge orifice height, it can be derived by using a mean wind speed reduction procedure after having knowledge of the roughness of the surrounding surface and the angular height of surrounding obstacles. A suggested scheme is shown in Annex 6.D.¹ This scheme is very site-dependent, and estimation requires a good knowledge of the station and gauge location. Shielded gauges catch more precipitation than their unshielded counterparts, especially for solid precipitation. Therefore, gauges should be shielded either naturally (for example, forest clearing) or artificially (for example, Alter, Canadian Nipher type, Tretyakov windshield) to minimize the adverse effect of wind speed on measurements of solid precipitation (for some information on shield design, refer to WMO, 1998, 2008). The type of windshield configuration, as well as gauge type, will alter the relationship between wind speeds and catch efficiency and have implications on data homogeneity.

Wetting loss (Sevruk, 1974*a*) is another cumulative systematic loss from manual gauges which varies with precipitation and gauge type; its magnitude is also a function of the number of times the gauge is emptied. Average wetting loss can be up to 0.2 mm per observation. At synoptic stations where precipitation is measured every 6 h, this can become a very significant loss. In some countries, wetting loss has been calculated to be 15 % to 20 % of the measured winter precipitation. Correction for wetting loss at the time of observation is a feasible alternative. Wetting loss can be kept low in a well-designed gauge. The methodology to determine the wetting loss of manual gauges (WMO, 1998) would suffice. It is recommended that the wetting loss for manual gauges be re-examined periodically (for example, every 5 years) as it tends to change with the age of the collector. The internal surfaces should be of a material which can be kept smooth and clean; paint, for example, is unsuitable, but baked enamel is satisfactory. Seams in the construction should be kept to a minimum.

Evaporation losses (Sevruk, 1974*b*) vary by gauge type, climatic zone and time of year (seasons mentioned below correspond to the northern hemisphere). Evaporation loss is a problem with gauges that do not have a funnel device in the bucket, especially in late spring at mid-latitudes. Losses of over 0.8 mm per day have been reported. Losses during winter are much less than during comparable summer months, ranging from 0.1 to 0.2 mm per day. These losses, however, are cumulative. In a well-designed gauge, only a small water surface is exposed, its ventilation is minimized, and the water temperature is kept low by a reflective outer surface. In storage and accumulating recording gauges, errors associated with evaporation can be virtually eliminated through the use of oil in the collector.

It is clear that, in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, corrections to the actual measurements are necessary. 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.

¹ A wind reduction scheme recommended by the Commission for Instruments and Methods of Observation at its eleventh session (1994).

6.5 RECORDING PRECIPITATION GAUGES

Recording precipitation automatically has the advantage that it can provide better time resolution than manual measurements, and it is possible to reduce the evaporation and wetting losses. These readings are of course subject to the wind effects discussed in 6.4.

Three types of automatic precipitation recorders are in general use, namely the weighing-recording type, the tilting or tipping-bucket type, and the float type. Only the weighing type is satisfactory for measuring all kinds of precipitation, while the use of the other two types being for the most part limited to the measurement of rainfall. Some other automatic gauges that measure precipitation without using moving parts are also available. These gauges use devices such as capacitance sensors, pressure transducers, acoustic and optical sensors, or small radar devices to provide an electronic signal that is proportional to the precipitation equivalent. The clock device that times intervals and that dates the time record is a very important component of the recorder.

Because of the high variability of precipitation intensity over a 1 min timescale, a single 1 min rainfall intensity value is not representative of a longer time period. Therefore, 1 min rainfall intensity should not be used in a temporal sampling scheme, such as one synoptic measurement every one or three hours. Very good time synchronization, better than 10 s, is required between the reference time and the different instruments of the observing station.

6.5.1 Weighing-recording gauge

6.5.1.1 Instruments

In these instruments, the weight of a container, together with the precipitation accumulated therein, is recorded continuously, either by means of a spring mechanism or with a system of balance weights. All precipitation, both liquid and solid, is recorded as it falls. This type of gauge normally has no provision for emptying itself; the capacity (namely, the maximum accumulation between recharge) ranges from 250 to 1 500 mm depending on the model. Low-capacity models should be avoided in areas where the maximum accumulation could occur over short periods of time. The gauges must be maintained to minimize evaporation losses, which can be accomplished by adding sufficient oil or other evaporation suppressants inside the container to form a film over the water surface. Any difficulties arising from oscillation of the balance in strong winds can be reduced 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 need to be melted before it can be recorded. For winter operation, the catchment container is charged with an antifreeze solution (see 6.3.2) to dissolve the solid contents. The amount of antifreeze depends on the expected amount of precipitation and the minimum temperature expected at the time of minimum dilution. These instruments do not use any moving mechanical parts in the weighing mechanism; only elastic deformation occurs. Therefore, mechanical degradation and the resulting need for maintenance are significantly reduced.

The digitized output signal is generally averaged and filtered. Precipitation intensity can also be calculated from the differences between two or more consecutive weight measurements. The accuracy of these types of gauges is related directly to their measuring and/or recording characteristics, which can vary with manufacturer.

Many instruments have data output that contain diagnostic parameters which are very useful for further evaluations of measured data and for data quality control.

Weighing technology combined with a self-emptying tipping-bucket enables high resolution and high precision measurements with a very small construction volume. This type of instrument measures the weight of water in a tipping-bucket with a volume of up to 20 ml and can determine smaller amounts of precipitation compared to "classic" tipping-bucket gauges (see 6.5.2).

6.5.1.2 Errors and corrections

Except for error due to the wetting loss in the container when it is emptied, weighing-recording gauges are susceptible to all of the other sources of error discussed in 6.4. It should also be noted that automatic recording gauges alone cannot identify the type of precipitation. A significant problem with this type of gauge is that precipitation, particularly freezing rain or wet snow, can stick to the inside of the gauge orifice and not fall into the bucket until later. This severely limits the ability of weighing-recording gauges to provide accurate timing of precipitation events. Another common fault with weighing-type gauges is wind pumping. This usually occurs during high winds when turbulent air currents passing over and around the catchment container cause oscillations in the weighing mechanism. Errors associated with such anomalous recordings can be minimized by averaging readings over short time intervals usually ranging from 1 to 5 min. Timing errors in the instrument clock may assign the catch to the wrong period or date. Some weighing-recording gauges may also exhibit some temperature sensitivity in the weighing mechanism that adds a component to the output which is proportional to the diurnal temperature cycle.

Some potential errors in manual methods of precipitation measurement can be eliminated or at least minimized by using weighing-recording gauges. Random measurement errors associated with human observer error and certain systematic errors, particularly evaporation and wetting loss, are minimized. In some countries, trace observations are officially given a value of zero, thus resulting in a biased underestimate of the seasonal precipitation total. This problem is minimized with weighing-type gauges, since even very small amounts of precipitation will accumulate over time.

A fundamental characteristic of weighing-recording gauges when measuring precipitation intensity is the response time (filtering process included), which leads to measurement errors (systematic delay). The response times, available in operation manuals or evaluated during a previous WMO intercomparison (WMO, 2009), are of the order of six seconds to a few minutes depending on the gauge's design and model. The 1 min precipitation intensity resolution of weighing-recording gauges can be very different from gauge to gauge and depends on the transducer resolution. Such gauges may also exhibit a limit or discrimination threshold for precipitation intensity.

The correction of weighing gauge data on an hourly or daily basis may be more difficult than on longer time periods, such as monthly climatological summaries. Ancillary data from automatic weather stations, such as wind at gauge height, air temperature, present weather or snow depth, will be useful in interpreting and correcting accurately the precipitation measurements from automatic gauges.

6.5.1.3 Calibration and maintenance

Weighing-recording gauges usually have few moving parts and, therefore, should seldom require calibration. Calibration commonly involves the use of a series of weights which, when placed in the bucket or catchment container, provide a predetermined value equivalent to an amount of precipitation. Calibrations should normally be done in a laboratory setting and should follow the manufacturer's instructions.

An alternative procedure for calibrating weighing-recording gauges when dealing with precipitation intensity measurements is given in Annex 6.D. This calibration, referred to as a dynamic calibration in steady-state conditions of the reference flow rates, is performed to evaluate the measurement errors of the weighing gauge. This procedure can also be used to assess the dynamic response of the weighing gauge by performing the classic step-response test, that is, by providing the instrument with a reference flow rate showing a single abrupt change from zero to a given equivalent rainfall rate. Moreover, the repeating of the dynamic calibration in unsteady conditions (time-varying reference flow rates as a simulation of real-world events) permits a finer calibration of weighing gauges (especially for systematic delays due to the instrument's response time) and could lead to improved dynamic performance and accuracy in real-world events (Colli et al., 2013b).

Routine maintenance should be conducted every three to four months, depending on precipitation conditions at the site. Both the exterior and interior of the gauge should be inspected for loose or broken parts and to ensure that the gauge is level. Any manual read-out should be checked against the removable data record to ensure consistency before removing and annotating the record. The bucket or catchment container should be emptied, inspected, cleaned, if required, and recharged with oil for rainfall-only operation or with antifreeze and oil if solid precipitation is expected (see 6.3.2). The recording device should be set to zero in order to make maximum use of the gauge range. The digital memory as well as the power supply should be checked and replaced, if required. Timing intervals and dates of record must be checked.

A proper field calibration, and field calibration check or field inspection should also be conducted on a regular basis as part of the routine maintenance and check, taking into account site and operational constraints. For rainfall intensity gauges, a recommended procedure by means of a portable device for reference flow rates is given in Annex 6.E.

6.5.2 Tipping-bucket gauge

The tipping-bucket raingauge is used for measuring accumulated totals and the rate of rainfall. Suitable intensity-dependent corrections (see 6.5.2.2) should be applied to improve the accuracy of the intensity measurements and to overcome the underestimation of intensity for high rainfall rates and the overestimation of intensity for low rainfall rates, both of which are typical in non-corrected tipping-bucket gauges.

6.5.2.1 Instruments

The principle behind the operation of this instrument is simple. A tipping-bucket raingauge uses a metallic or plastic twin bucket balance to measure the incoming water in portions of equal weight. When one bucket is full, its centre of mass is outside the pivot and the balance tips, dumping the collected water and bringing the other bucket into position to collect. The bucket compartments are shaped in such a way that the water is emptied from the lower one. The water mass content of the bucket is constant (m [g]). Therefore, by using the density of water ($\rho = 1 \text{ g/cm}^3$), the corresponding volume (V [cm^3]) is derived from the weight of the water and, consequently, the corresponding accumulation height (h [mm]) is retrieved by using the area of the collector (S [cm^2]). The equation is:

$$V = m/\rho = h \cdot S \quad (6.2)$$

Thus, by using the density of water, h is calculated, where 1 mm corresponds to 1 g of water over an area of 10 cm^2 . To have detailed records of precipitation, the amount of rain should not exceed 0.2 mm. For a gauge area of 1 000 cm^2 , this corresponds to a bucket content of 20 g of water.

The raw output is a contact closure (reed switch or relay contact), so each tip produces an electrical impulse as a signal output which must be recorded by a data logger or an analogue-to-digital converter (data acquisition system equipped with reed switch reading ports). This mechanism provides a continuous measurement without manual interaction.

The rainfall intensity of non-corrected tipping-bucket gauges is calculated based on the number of tips in a periodic sampling rate (typically 6 or 10 s) and averaged over a chosen time interval (for example, 1 min). In this way, an intensity value is available every minute that represents the intensity of the past minute or minutes. This sampling scheme reduces the uncertainty of the average. In addition, the rainfall intensity resolution depends on the size of the bucket and the chosen time interval. For example, a tip equivalent to 0.2 mm leads to a 1 min rainfall intensity resolution of 12 mm h^{-1} which is constant over the measurement range of the gauge if no intensity-dependent corrections are applied.

The bucket takes a small but finite time to tip and, during the first half of its motion, additional rain may enter the compartment that already contains the calculated amount of rainfall. The water losses during the tipping movement indicate a systematic mechanical error that is rather a

function of the intensity itself and can be appreciable during heavy rainfall ($> 100 \text{ mm h}^{-1}$). However, this can be corrected by using a calibration procedure as given in Annex 6.C and applying a correction curve or algorithm (see 6.4). An alternative simple method is to use a device like a siphon at the foot of the funnel to direct the water to the buckets at a controlled rate. This smoothes out the intensity peaks of very short-period rainfall. Alternatively, a device can be added to accelerate the tipping action; essentially, a small blade is impacted by the water falling from the collector and is used to apply an additional force to the bucket, varying with rainfall intensity.

The tipping-bucket gauge is particularly convenient for automatic weather stations because it lends itself to digital methods. The pulse generated by a contact closure can be monitored by a data logger, preferably including the time the tips occurred, to calculate a corrected rainfall intensity, which can then be used to retrieve the precipitation amount over selected periods. It may also be used with a chart recorder.

6.5.2.2 Errors and corrections

Since the tipping-bucket raingauge has sources of error which differ somewhat from those of other gauges, special precautions and corrections are advisable. Some sources of error include the following:

- (a) The loss of water during the tipping action in heavy rain; this can be considerably reduced by conducting a dynamic calibration (see Annex 6.C) and applying an intensity-dependent correction;
- (b) With the usual bucket design, the exposed water surface is large in relation to its volume, meaning that appreciable evaporation losses can occur, especially in hot regions. This error may be 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;
- (d) Water may adhere to both the walls and the lip of the bucket, resulting in rain residue in the bucket and additional weight to be overcome by the tipping action. Tests on waxed buckets produced a 4 % reduction in the volume required to tip the balance compared with non-waxed buckets. Volumetric calibration can change, without adjustment of the calibration screws, by variation of bucket wettability through surface oxidation or contamination by impurities and variations in surface tension;
- (e) The stream of water falling from the funnel onto the exposed bucket may cause over-reading, depending on the size, shape and position of the nozzle;
- (f) The instrument is particularly prone to bearing friction and to having an improperly balanced bucket because the gauge is not level;
- (g) The limited repeatability at various rainfall intensities of the inter-tip time interval due to low stability of the mechanics of the buckets (that is bucket movement) degrades the measurements; this systematic mechanical effect can be investigated by means of specific tests recording a series of inter-tip time intervals that make it possible to estimate the mechanical precision of the bucket (see Colli et al., 2013b); such errors may be reduced by improving the construction quality of the gauges;
- (h) The sampling errors of tipping-bucket gauges (Habib et al., 2001) have an additional strong impact on field performance under light precipitation regimes; these errors consist in a delay of the tipping-bucket mechanism in assigning the collected amount of water to the corresponding time interval; different calculation techniques exist for reducing the impact of

sampling errors and providing rainfall intensity measurements at a higher resolution than the tipping-bucket gauges' sensitivity would allow (see Colli et al., 2013a).

Careful calibration can provide corrections for the systematic parts of these errors. Effective corrections for improving the measurement of rainfall intensity (WMO, 2009), and consequently the corresponding accumulated amount, consist in performing a dynamic calibration and applying correction curves (see 6.4), for example, by applying a software correction or an algorithm in the data acquisition system. Alternatively, they can involve conducting a linearization procedure in the instrument's electronics circuit (generating an intensity-dependent emission of extra pulses) or through a mechanism (for example, small deflectors that induce a dynamic pressure which increases with intensity, allowing the tip to occur before the bucket is full). In WMO (2009), it is shown that linearization by extra electronic pulses is well suited for measuring precipitation amount but less so for measuring intensity. On the other hand, mechanical linearization compensates for the loss of water during the movement of the balance and greatly minimizes the intensity underestimation during high-rate events. The software correction (correction curve or algorithm) resulted in being the most effective method for correcting systematic mechanical errors.

The measurements from tipping-bucket raingauges may be corrected for effects of exposure in the same way as other types of precipitation gauge.

Heating devices can be used to allow for measurements during the cold season, particularly of solid precipitation. However, the performance of heated tipping-bucket gauges can be poor as a result of large errors due to both wind and evaporation of melting snow. Therefore, other types of gauges should be considered for use in winter precipitation measurement in regions where temperatures fall below 0 °C for prolonged periods. However, the evaporation effect can be minimized by using instruments with controlled heating elements that maintain the temperature of the critical parts slightly above the melting point of water.

6.5.2.3 Calibration and maintenance

Calibration of the tipping bucket is usually accomplished by passing a known amount of water through the tipping mechanism at various rates and by adjusting the mechanism to the known volume. This procedure should be followed under laboratory conditions. The recommended calibration procedure for these gauges is available in Annex 6.C.

A proper field calibration, and field calibration check or field inspection should also be conducted on a regular basis as part of the routine maintenance and check, taking into account site and operational constraints. For catchment type rainfall intensity gauges, a recommended procedure by means of a portable device for reference flow rates is given in Annex 6.E.

Owing to the numerous error sources, the collection characteristics and calibration of tipping-bucket raingauges are a complex interaction of many variables. Daily comparisons with the standard raingauge can provide useful correction factors, and is good practice. The correction factors may vary from station to station. Correction factors are generally greater than 1.0 (under-reading) for low-intensity rain, and less than 1.0 (over-reading) for high-intensity rain. The relationship between the correction factor and intensity is not linear but forms a curve.

Routine maintenance should include cleaning the accumulated dirt and debris from funnel and buckets, as well as ensuring that the gauge is level. It is highly recommended that the tipping mechanism be replaced with a newly calibrated unit on an annual basis. Timing intervals and dates of records must be checked.

6.5.3 Float gauge

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 a pen on a chart or a digital transducer. By suitably

adjusting the dimensions of the collector orifice, the float and the float chamber, any desired chart scale can be used.

In order to provide a record over a useful period (24 h are normally required) either the float chamber has to be very large (in which case a compressed scale on the chart or other recording medium is obtained), or a mechanism must be provided for emptying the float chamber automatically and quickly whenever it becomes full, so that the chart pen or other indicator returns to zero. Usually a siphoning arrangement is used. The actual siphoning process should begin precisely at the predetermined level 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 s. In some instruments, the float chamber assembly is mounted on knife edges so that the full chamber overbalances; the surge of the water assists 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 5 s. One type of forced siphon has a small chamber that is separate from the main chamber and accommodates the rain that falls during siphoning. This chamber empties into the main chamber when siphoning ceases, thus 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 that water might freeze in the float chamber 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 in order to prevent freezing, because the heat may reduce the accuracy of the observations by stimulating vertical air movements above the gauge and increasing evaporation losses.

A large undercatch by unshielded heated gauges, caused by the wind and the evaporation of melting snow, has been reported in some countries, as is the case for weighing gauges (see 6.5.1.2).

Apart from the fact that calibration is performed using a known volume of water, the maintenance procedures for this gauge are similar to those of the weighing-recording gauge (see 6.5.1.3).

6.5.4 Other rain gauges

With the growth of measurement electronics technologies and smart instruments, other precipitation instruments have been developed in recent years. Their performance is approximately of the same quality as performance of conventional tipping bucket rain gauges. However, those instruments provide rain intensity with higher resolution comparing to classic methods, starting from 0.01 mm, and are particularly suitable for areas which are difficult to access due to being less maintenance demanding devices. These are described in Volume I, Chapter 14.

6.6 MEASUREMENT OF DEW, ICE ACCUMULATION AND FOG PRECIPITATION

6.6.1 Measurement of dew and leaf wetness

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. The exposure of plant leaves to liquid moisture from dew, fog and precipitation also plays an important role in plant disease, insect activity, and the harvesting and curing of crops.

In order to assess the hydrological contribution of dew, it is necessary to distinguish between dew formed:

- (a) As a result of the downward transport of atmospheric moisture condensed on cooled surfaces, known as dew-fall;
- (b) By water vapour evaporated from the soil and plants and condensed on cooled surfaces, known as distillation dew;
- (c) As water exuded by leaves, known as guttation.

All three forms of dew may contribute simultaneously to the observed dew, although only the first provides additional water to the surface, and the latter usually results in a net loss. 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.

The amount of dew deposited on a given surface in a stated period is usually expressed in units of kg m^{-2} or in millimetres depth of dew. Whenever possible, the amount should be measured to the nearest tenth of a millimetre.

Leaf wetness may be described as light, moderate or heavy, but its most important measures are the time of onset or duration.

A review of the instruments designed for measuring dew and the duration of leaf wetness, as well as a bibliography, is given in WMO (1992*b*).

The following methods for the measurement of leaf wetness are considered.

The amount of dew depends critically on the properties of the surface, such as its radiative properties, size and aspect (horizontal or vertical). It may be measured by exposing a plate or surface, which can be natural or artificial, with known or standardized properties, and assessing the amount of dew by weighing it, visually observing it, or making use of some other quantity such as electrical conductivity. The problem lies in the choice of the surface, because the results obtained instrumentally are not necessarily representative of the dew deposit on the surrounding objects. Empirical relationships between the instrumental measurements and the deposition of dew on a natural surface should, therefore, be established for each particular set of surface and exposure conditions; empirical relationships should also be established to distinguish between the processes of dew formation if that is important for the particular application.

A number of instruments are in use for the direct measurement of the occurrence, amount and duration of leaf wetness and dew. 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 resulting from 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 instruments providing a continuous trace, it is possible to distinguish between moisture deposits caused by fog, dew or rain by considering the type of trace. The only certain method of measuring net dew-fall by itself is through the use of a very sensitive lysimeter (see Volume I, Chapter 10).

In WMO (1992*b*) two particular electronic instruments for measuring leaf wetness are advocated for development as reference instruments, and various leaf-wetting simulation models are proposed. Some use an energy balance approach (the inverse of evaporation models), while others use correlations. Many of them require micrometeorological measurements. Unfortunately, there is no recognized standard method of measurement to verify them.

6.6.2 Measurement of ice accumulation

Ice can accumulate on surfaces as a result of several phenomena. Ice accumulation from freezing precipitation, often referred to as glaze, is the most dangerous type of icing condition. It may cause extensive damage to trees, shrubs and telephone and power lines, and create hazardous conditions on roads and runways. Hoar frost (commonly called frost) forms when air with a

dewpoint temperature below freezing is brought to saturation by cooling. Hoar frost is a deposit of interlocking ice crystals formed by direct sublimation on objects, usually of small diameter, such as tree branches, plant stems, leaf edges, wires, poles, and so forth. Rime is a white or milky and opaque granular deposit of ice formed by the rapid freezing of supercooled water drops as they come into contact with an exposed object.

6.6.2.1 Measurement methods

At meteorological stations, the observation of ice accumulation is generally more qualitative than quantitative, primarily due to the lack of a suitable sensor. Ice accretion indicators, usually made of anodized aluminium, are used to observe and report the occurrence of freezing precipitation, frost or rime icing.

Observations of ice accumulation can include both the measurement of the dimensions and the weight of the ice deposit as well as a visual description of its appearance. These observations are particularly important in mountainous areas where such accumulation on the windward side of a mountain may exceed the normal precipitation. 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 disc, 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 disc 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 to 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.

In the ISO 12494:2017 standard (ISO, 2007), which applies to ice accretion on all kinds of structures except electrical overhead line conductors, a standard ice-measuring device is described as follows:

- (a) A smooth cylinder with a diameter of 30 mm placed with the axis vertical and rotating around the axis. The cylinder length should be a minimum of 0.5 m, but, if heavy ice accretion is expected, the length should be 1 m;
- (b) The cylinder is placed 10 m above terrain;
- (c) Recordings of ice weight may be performed automatically.

In Fikke et al. (2007), several types of ice detectors are identified, some of which are used for the start and end of icing periods while others are also able to quantify the ice accretion rate (usually expressed in $\text{kg m}^{-2} \text{h}^{-1}$). Many sensors are based on the measurement of the ice mass on a vertical tube used as a target for icing. An optical sensor (infrared beam) detects the change of reflecting properties of a target tube when covered with ice. Another sensor, widely used for freezing rain, consists of a vibrating probe. Ice accreted on this probe changes the vibrating frequency, which allows both the detection of icing conditions and an estimate of the ice accretion rate. An internal probe heater is applied to melt the ice and keep the sensor within its operational limits.

6.6.2.2 *Ice on pavements*

Sensors have been developed and are in operation to detect and describe ice on roads and runways, and to support warning and maintenance programmes. Volume III, Chapter 10 provides more specific information on this subject.

With a combination of measurements, it is possible to detect dry and wet snow and various forms of ice. One sensor using two electrodes embedded in the road, flush with the surface, measures the electrical conductivity of the surface and readily distinguishes between dry and wet surfaces. A second measurement, of ionic polarizability, determines the ability of the surface, to hold an electrical charge; a small charge is passed between a pair of electrodes for a short time, and the same electrodes measure the residual charge, which is higher when there is an electrolyte with free ions, such as salty water. The polarizability and conductivity measurements together can distinguish between dry, moist and wet surfaces, frost, snow, white ice and some de-icing chemicals. However, because the polarizability of the non-crystalline black ice is indistinguishable from water under some conditions, the dangerous black ice state can still not be detected with the two sensors. In at least one system, this problem has been solved by adding a third specialized capacitive measurement which detects the unique structure of black ice.

The above method is a passive technique. There is an active in situ technique that uses either a heating element, or both heating and cooling elements, to melt or freeze any ice or liquid present on the surface. Simultaneous measurements of temperature and of the heat energy involved in the thaw-freeze cycle are used to determine the presence of ice and to estimate the freezing point of the mixture on the surface.

Most in situ systems include a thermometer to measure the road surface temperature. The quality of the measurement depends critically on the mounting (especially the materials) and exposure, and care must be taken to avoid radiation errors.

There are two remote-sensing methods under development which lend themselves to car-mounted systems. The first method is based on the reflection of infrared and microwave radiation at several frequencies (about 3 000 nm and 3 GHz, respectively). The microwave reflections can determine the thickness of the water layer (and hence the risk of aquaplaning), but not the ice condition. Two infrared frequencies can be used to distinguish between dry, wet and icy conditions. It has also been demonstrated that the magnitude of reflected power at wavelengths around 2 000 nm depends on the thickness of the ice layer.

The second method applies pattern recognition techniques to the reflection of laser light from the pavement, to distinguish between dry and wet surfaces, and black ice.

6.6.3 **Measurement of fog precipitation**

Fog consists of minute water droplets suspended in the atmosphere to form a cloud at the Earth's surface. Fog droplets have diameters from about 1 to 40 μm and fall velocities from less than 1 to approximately 5 cm s^{-1} . In fact, the fall speed of fog droplets is so low that, even in light winds, the drops will travel almost horizontally. When fog is present, horizontal visibility is less than 1 km; it is rarely observed when the temperature and dewpoint differ by more than 2 $^{\circ}\text{C}$.

Meteorologists are generally more concerned with fog as an obstruction to vision than as a form of precipitation. However, from a hydrological standpoint, some forested high-elevation areas experience frequent episodes of fog as a result of the advection of clouds over the surface of the mountain, where the consideration of precipitation alone may seriously underestimate the water input to the watershed (Stadtmuller and Agudelo, 1990). More recently, the recognition of fog as a water supply source in upland areas (Schemenauer and Cereceda, 1994a) and as a wet deposition pathway (Schemenauer and Cereceda, 1991; Vong et al., 1991) has led to the requirement for standardizing methods and units of measurement. The following methods for the measurement of fog precipitation are considered.

Although there have been a great number of measurements for the collection of fog by trees and various types of collectors over the last century, it is difficult to compare the collection rates quantitatively. The most widely used fog-measuring instrument consists of a vertical wire mesh cylinder centrally fixed on the top of a raingauge in such a way that it is fully exposed to the free flow of the air. The cylinder is 10 cm in diameter and 22 cm in height, and the mesh is 0.2 cm by 0.2 cm (Grunow, 1960). The droplets from the moisture-laden air are deposited on the mesh and drop down into the gauge collector where they are measured or registered in the same way as rainfall. Some problems with this instrument are its small size, the lack of representativeness with respect to vegetation, the storage of water in the small openings in the mesh, and the ability of precipitation to enter directly into the raingauge portion, which confounds the measurement of fog deposition. In addition, the calculation of fog precipitation by simply subtracting the amount of rain in a standard raingauge (Grunow, 1963) from that in the fog collector leads to erroneous results whenever wind is present.

An inexpensive, 1 m² standard fog collector and standard unit of measurement is proposed by Schemenauer and Cereceda (1994*b*) to quantify the importance of fog deposition to forested high-elevation areas and to measure the potential collection rates in denuded or desert mountain ranges. The collector consists of a flat panel made of a durable polypropylene mesh and mounted with its base 2 m above the ground. The collector is coupled to a tipping-bucket raingauge to determine deposition rates. When wind speed measurements are taken in conjunction with the fog collector, reasonable estimates of the proportions of fog and rain being deposited on the vertical mesh panel can be taken. The output of this collector results in litres of water. Since the surface area is 1 m², this gives a collection in l m⁻².

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ANNEX 6.A. STANDARD REFERENCE RAINGAUGE PIT

Reference raingauges are installed in a well-drained pit according to the design and specifications reported in the EN 13798:2010 standard (CEN, 2010) to minimize environmental interference on measured rainfall intensities and protect against in-splash by a metal or plastic grating. The buried or sunken gauge (see Koschmider, 1934; Sieck et al., 2007) is expected to show a higher rainfall reading than a gauge above ground, with possible differences of 10 % or more, when both instruments are working perfectly and accurately. Pits are preferably sited on ground level to avoid possible surface runoff (see general configuration in Figure 6.A.1). The pit should be deep

enough to accommodate the raingauge and to level the gauge's collector with the top of the grating (ground level) and centre it. The design of the pit takes into account dimensions of the raingauge and its method of installation. The base of the pit should have a recess (extra pit) to allow water to be drained. The square space of the grating is also adapted according to the raingauge collector's diameter in order to satisfy the standard requirements reported in CEN (2010). The sides of the pit are formed of bricks and concrete and are supported to prevent collapse. Supporting walls are built around the edges and a grating of approximately 1 875 x 1 875 x 120 mm (L x W x H) is installed on the pit walls with the possibility to be lifted to give access to the raingauge for checks and maintenance operations. The grating distance is approximately 120–125 mm. The grating is strong enough to walk on, to maintain its shape without distortion. To prevent in-splash from the top surface of the grating, the strips of the grating are at least 2 mm thick and the distance between the edge of the central square and the ground is greater than 600 mm (for further details see CEN, 2010). In Figure 6.A.1, an example of a realization of four standard reference raingauge pits is provided, as reported in WMO (2009).

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Figure 6.A.1. A raingauge pit and its grating (ground level configuration)

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Figure 6.A.2. Realization of the reference raingauge pits at Vigna di Valle, Italy (2007) during the WMO Field Intercomparison of Rainfall Intensity Gauges

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ANNEX 6.B. PRECIPITATION INTERCOMPARISON SITES

The following text regarding precipitation intercomparison sites is based on statements made by the Commission for Instruments and Methods of Observation at its eleventh session in 1994 and updated following its fifteenth session in 2010:

The Commission recognized the benefits of national precipitation sites or centres where past, current and future instruments and methods of observation for precipitation can be assessed on an ongoing basis at evaluation stations. These stations should:

- (a) Operate the WMO recommended gauge configurations for rain (Reference Raingauge Pit) and snow (Double Fence Intercomparison Reference (DFIR)). Installation and operation will follow specifications of the WMO precipitation intercomparisons. A DFIR installation is not required when only rain is observed;
- (b) Operate past, current and new types of operational precipitation gauges or other methods of observation according to standard operating procedures and evaluate the accuracy and performance against WMO recommended reference instruments;
- (c) Take auxiliary meteorological measurements which will allow the development and tests for the application of precipitation correction procedures;

- (d) Provide quality control of data and archive all precipitation intercomparison data, including the related meteorological observations and the metadata, in a readily acceptable format, preferably digital;
- (e) Operate continuously for a minimum of 10 years;
- (f) Test all precipitation correction procedures available (especially those outlined in the final reports of the WMO intercomparisons) on the measurement of rain and solid precipitation;
- (g) Facilitate the conduct of research studies on precipitation measurements. It is not expected that the centres provide calibration or verification of instruments. They should make recommendations on national observation standards and should assess the impact of changes in observational methods on the homogeneity of precipitation time series in the region. The site would provide a reference standard for calibrating and validating radar or remote-sensing observations of precipitation.

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ANNEX 6.C. STANDARDIZED PROCEDURE FOR LABORATORY CALIBRATION OF CATCHMENT TYPE RAINFALL INTENSITY GAUGES

1. Principles

The calibration laboratory should be well prepared to perform calibrations of instruments to be used for operational practices. Apart from a well-designed reference system, the calibration procedures should be documented in full detail and set-up and staff should be well prepared before starting any calibration activity (see the ISO/IEC 17025 standard (ISO/IEC, 2017) for details). The result of any calibration will be a calibration certificate presenting the results of the calibration (including corrections to be applied), allowing a compliance check with the relevant WMO recommendations.

This certificate should also contain the measurement uncertainty for rainfall intensity. It should document the traceability of the rainfall intensity reference, the environmental conditions, such as temperature, and the applied time-averaging method.

Rainfall intensity gauges should be calibrated using a calibration system that:

- (a) Has the capability of generating a constant water flow at various flow rates corresponding to the entire operational range of measurement (recommended range: from 0.2 mm h⁻¹ up to 2 000 mm h⁻¹);
- (b) Is able to measure the flow by weighing the amount of water over a given period of time;
- (c) Is able to measure the output of the calibrated instrument at regular intervals or when a pulse occurs, which is typical for the majority of tipping-bucket raingauges.

2. Requirements

- (a) The calibration system should be designed to obtain uncertainties less than 1 % for the generated rainfall intensity, and such performances should be reported and detailed;

- (b) In case of tipping-bucket raingauges, correct and suitable balancing of the buckets should be verified in order to guarantee a minimal variance of the tipping duration during the measurement process;
- (c) At least five reference intensities suitably spaced to cover the whole operating range of the instrument should be used;
- (d) The number of rainfall intensity reference setting points should be large enough to be able to determine a fitting curve by interpolation. The reference setting should be selected and well spaced so that the calibration curve can be established by interpolation in such a way that the uncertainty of the fitting curve is less than the required measurement uncertainty for the full range;
- (e) The calculation of flow rate is based on the measurements of mass and time;
- (f) The measurement of mass is better than 0.1 %;
- (g) The duration of any test should be long enough to guarantee an uncertainty of less than 1 % on the generated intensity;
- (h) The maximum time resolution for the measurement of rainfall intensities should be 1 s;
- (i) The following issues must be considered for any related laboratory activity in addressing possible error sources:
 - (i) The water quality/purity used for calibration should be well defined;
 - (ii) The reproducibility of the calibration conditions should be a priority;
 - (iii) Suitable control and recording equipment should be used (such as PC-controlled);
 - (iv) All acquisition systems must comply with electromagnetic compatibility to avoid parasitic pulses;
- (j) The quantity, for which measurements of precipitation are generally reported, is height expressed in millimetres although weighing gauges measure mass. Since the density of rain depends on ambient temperature, the relationship between mass and the equivalent height of rainfall introduces an inaccuracy that must be taken into account during calibration and uncertainty calculation;
- (k) The environmental conditions during each calibration must be noted and recorded:
 - (i) Date and hour (start/end);
 - (ii) Air temperature [$^{\circ}\text{C}$];
 - (iii) Water temperature [$^{\circ}\text{C}$];
 - (iv) Atmospheric pressure [hPa];
 - (v) Ambient relative humidity [%];
 - (vi) Any special condition that may be relevant to calibration (for example, vibrations);
 - (vii) Evaporation losses must be estimated [mm];
- (l) The number of tests performed for each instrument, their description in terms of time units and/or number of tips must be documented.

3. Procedure from data interpretation

- (a) The results should be presented in the form of a graph where the relative error is plotted against the reference intensity. The relative error is evaluated for each reference flow rate as:

$$e = \frac{I_m - I_r}{I_r} \cdot 100\%$$

where I_m is the intensity measured by the instrument and I_r the actual reference intensity provided to the instrument;

- (b) Ideally five tests, but a minimum of three, should be performed for each set of reference intensities, so that five error figures are associated with each instrument. The average error and the average values of I_r and I_m are obtained by discarding the minimum and the maximum value of e obtained for each reference flow rate, then evaluating the arithmetic mean of the three remaining errors and reference intensity values. For each reference intensity, an error bar encompassing all the five error values used to obtain the average figures should be reported;
- (c) In addition, I_r versus I_m can be plotted, where I_m and I_r are average values, calculated as indicated above; all data are fitted with an interpolating curve, obtained as the best fit (linear, power law or second order polynomial are acceptable);
- (d) In the graphs presenting the results, the $\pm 5\%$ limits must be drawn to allow an easy comparison of the results with the WMO recommendations;
- (e) In case water storage should occur for an intensity below the maximum declared intensity, the intensity at which water storage begins should be documented in the calibration certificate and intensities above this limit should not be considered;
- (f) In addition to measurements based on constant flow rates, the step response of each non-tipping-bucket raingauge instrument should be determined. The step response should be measured by switching between two different constant flows, namely from 0 mm h^{-1} to the reference intensity and back to 0 mm h^{-1} . The constant flow should be applied until the output signal of the instrument is stabilized, that is, when the further changes or fluctuation in the established rainfall intensity can be neglected with respect to the stated measurement uncertainty of the reference system. The sampling rate must be at least one per minute for those instruments that allow it. The time before stabilization is assumed as a measure of the delay of the instrument in measuring the reference rainfall intensity. Less than one minute delay is required for accurate rainfall intensity measurements. The response time should always be documented in the calibration certificate.

4. Uncertainty calculation

The following sources of the measurement uncertainty should be considered and quantified:

- (a) Flow generator: Uncertainty on the flow steadiness deriving from possible variations in the constant flow generation mechanism, including pressure difference inside water content and in distribution pipes;
- (b) Flow measuring devices (both reference and device under calibration): Uncertainties due to the weighing apparatus, to time measurement and delays in acquisition and data processing and to the variation of experimental and ambient conditions such as temperature and relative humidity.

These two sources of uncertainty are independent from each other; therefore a separate analysis can be performed, and results can be then combined into the uncertainty budget.

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ANNEX 6.D. SUGGESTED CORRECTION PROCEDURES FOR PRECIPITATION MEASUREMENTS

The following text regarding the correction procedures for precipitation measurements is based on statements made by the Commission for Instruments and Methods of Observation at its eleventh session in 1994:

The correction methods are based on simplified physical concepts as presented in WMO (1987). They depend on the type of precipitation gauge applied. The effect of wind on a particular type of gauge has been assessed by using intercomparison measurements with the WMO reference gauges – the pit gauge for rain and the Double Fence Intercomparison Reference (DFIR) for snow as is shown in WMO (1984) and by the results of the WMO Solid Precipitation Measurement Intercomparison (WMO, 1998). The reduction of wind speed to the level of the gauge orifice should be made according to the following formula:

$$u_{hp} = (\log h z_0^{-1}) \cdot (\log H z_0^{-1})^{-1} \cdot (1 - 0.024\alpha) u_H$$

where u_{hp} is the wind speed at the level of the gauge orifice; h is the height of the gauge orifice above ground; z_0 is the roughness length (0.01 m for winter and 0.03 m for summer); H is the height of the wind speed measuring instrument above ground; u_H is the wind speed measured at the height H above ground; and α is the average vertical angle of obstacles around the gauge.

The latter depends on the exposure of the gauge site and can be based either on the average value of direct measurements, on one of the eight main directions of the wind rose of the vertical angle of obstacles (in 360°) around the gauge, or on the classification of the exposure using metadata as stored in the archives of Meteorological Services. The classes are as follows:

TABLE: Table horizontal lines

<i>Class</i>	<i>Angle</i>	<i>Description</i>
Exposed site	0–5	Only a few small obstacles such as bushes, group of trees, a house
Mainly exposed site	6–12	Small groups of trees or bushes or one or two houses
Mainly protected site	13–19	Parks, forest edges, village centres, farms, group of houses, yards
Protected site	20–26	Young forest, small forest clearing, park with big trees, city centres, closed deep valleys, strongly rugged terrain, leeward of big hills

Wetting losses occur with the moistening of the inner walls of the precipitation gauge. They depend on the shape and the material of the gauge, as well as on the type and frequency of precipitation. For example, for the Hellmann gauge they amount to an average of 0.3 mm on a rainy and 0.15 mm on a snowy day; the respective values for the Tretyakov gauge are 0.2 mm and 0.1 mm. Information on wetting losses for other types of gauges can be found in WMO (1982).

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ANNEX 6.E. PROCEDURE FOR FIELD CALIBRATION OF CATCHMENT TYPE RAINFALL INTENSITY GAUGES

The field calibration is part of a routine field maintenance and check and should be performed on a regular basis. Its main purpose is to verify the operational status of precipitation gauges: to detect malfunctions, output anomalies and calibration drifts over time or between two laboratory calibrations. Field calibrations also provide valuable insight for data analysis and interpretation. The procedure is based on the same principles as laboratory calibration (given in Annex 6.C), using the generation of constant intensity (stationary reference flow) within the gauge's range of operational use.

A field calibrator is typically composed of a cylindrical water tank of suitable capacity, a combination of air intakes and output nozzles for different rainfall intensities, and an electronic system to calculate the emptying time (see figure below). A suitable combination of air intakes and nozzles must be selected based on the precipitation gauge collector size and the intensity value chosen for the calibration. By opening the top tap and bottom nozzle, a constant flow is conveyed to the funnel of the gauge and, through the time of emptying and the conversion table (volume–time–intensity), it is possible to retrieve the reference intensity. Air intakes provide the pressure compensation, thus maintaining a constant push.

ELEMENT 9: Floating object (Automatic)

ELEMENT 10: Picture inline fixed size NO space

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A simplified scheme of a portable field calibrator

END ELEMENT

From an operational viewpoint, the portable field calibrator permits rapid tests due to its very simple operation. The calibrator does not contain any sophisticated components and therefore provides a cost-effective solution for the metrological verification of precipitation intensity instruments.

The repeatability of the field calibrator (and its accuracy) should be rigorously assessed in a laboratory before the operational use. The uncertainty should preferably be expressed as relative expanded uncertainty in relation to the statistical coverage interval (95 % confidence level, $k = 2$) and should be lower than 2 %.

A statistical analysis of relative errors with respect to the field reference flow of the calibrator should be conducted for each field-calibrated precipitation gauge. At least 25–30 data points (normally 1 min intensity values in mm h^{-1}) should be recorded for each reference intensity (selected by the field calibrator). This makes it possible to assume a normal distribution of the data around the mean value and to better estimate the average and improve the accuracy of the results (central limit theorem). All tests must be performed in environmental conditions without precipitation or fog and with low wind flows (to avoid dynamic pressure perturbations to air intakes). The reference intensity should always be started at the beginning of a minute synchronized with the instrument clock or data-logger timer (official/station time-stamp).

The minimum set of statistical parameters and metadata to be reported after each field calibration is listed below:

- (a) Date and time;

- (b) Reference intensity in mm h^{-1} (I_{ref}): constant intensity generated by the field calibrator;
- (c) Average ($\text{avg}I$) of intensity values ($I_{1\text{min}}$) in mm h^{-1} of the precipitation gauge during the calibration, calculated as follows:

$$\text{avg}I = \frac{1}{N} \sum_{j=1}^N (I_{1\text{min}}^j) \quad (6.E.1)$$

- (d) Extremes (namely $I_{+\text{CL}95\%}$, $I_{-\text{CL}95\%}$) of an interval $[\text{avg}I - \delta(95\%); \text{avg}I + \delta(95\%)] = [I_{+\text{CL}95\%}; I_{-\text{CL}95\%}]$ corresponding to the 95 % confidence level. The amplitude $\delta(95\%)$ is the half-width of the confidence interval calculated according to a normal or Student's t probability distribution of samples (it includes a calculation of the standard deviation);
- (e) Relative error in percentage of the average intensity, calculated as follows:

$$RE_{\text{avg}I} = 100 \cdot \left(\frac{\text{avg}I - I_{\text{ref}}}{I_{\text{ref}}} \right) \quad (6.E.2)$$

- (f) Relative errors in percentage of $I_{+\text{CL}95\%}$ and $I_{-\text{CL}95\%}$, calculated as follows:

$$RE_{+\text{CL}95\%} = 100 \cdot \left(\frac{I_{+\text{CL}95\%} - I_{\text{ref}}}{I_{\text{ref}}} \right) \quad (6.E.3)$$

$$RE_{-\text{CL}95\%} = 100 \cdot \left(\frac{I_{-\text{CL}95\%} - I_{\text{ref}}}{I_{\text{ref}}} \right) \quad (6.E.4)$$

The last three statistical parameters are used to calculate the gauge's relative errors with regard to intensity with an uncertainty interval at the 95 % confidence level for each reference intensity used during the calibration. The regular repetition of the field calibration and the comparison of results makes it possible to evaluate the stability of the calibration status and possible anomalies.

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