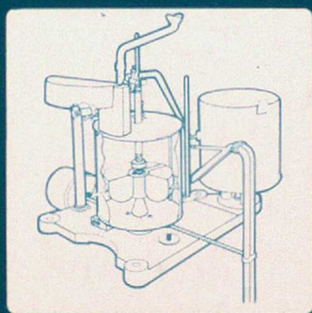
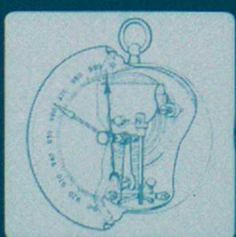
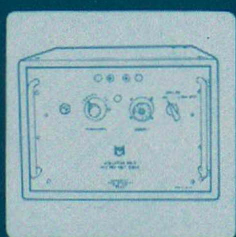
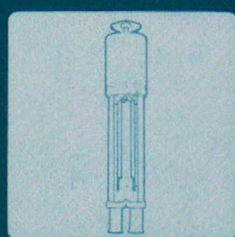
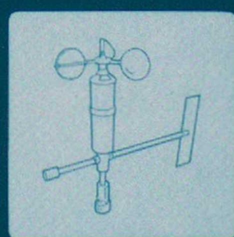
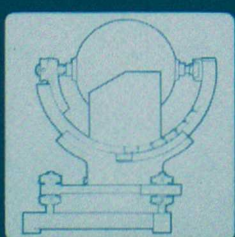
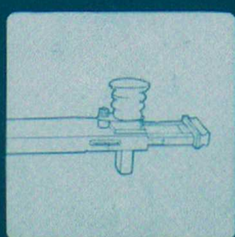
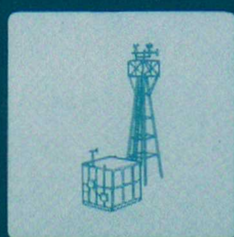
Meteorological Office

Handbook of Meteorological Instruments

Second Edition

5 Measurement of Precipitation and Evaporation



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METEOROLOGICAL OFFICE

HANDBOOK OF METEOROLOGICAL INSTRUMENTS

SECOND EDITION

VOLUME 5

MEASUREMENT OF PRECIPITATION AND EVAPORATION

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INTRODUCTION

The first edition of the *Handbook of meteorological instruments* was prepared by the Instruments Division of the Meteorological Office in 1953, to provide a comprehensive source of information on the design, installation, operation and maintenance of all instruments then in use at Meteorological Office stations. Since then numerous improvements have been made to existing instruments, and new instruments and instrument systems introduced into service. This revised edition, whilst retaining some of the original material, gives information on the more recently developed instruments, and records the modifications made to some of the instruments previously described. In general, only instruments currently in use are included and if information is required on older, obsolete, types reference should be made to the previous edition.

Initially, eight separate volumes, each dealing with a specific aspect of meteorological instrumentation for surface observations, are being presented as follows:

Volume 1 Measurement of Atmospheric Pressure
Volume 2 Measurement of Temperature
Volume 3 Measurement of Humidity
Volume 4 Measurement of Surface Wind
Volume 5 Measurement of Precipitation and Evaporation
Volume 6 Measurement of Sunshine and Solar and Terrestrial Radiation
Volume 7 Measurement of Visibility and Cloud Height
Volume 8 General Observational Systems

When complete, the set can be bound to form one book.

Although this handbook is intended primarily to provide information for Meteorological Office personnel about the instruments used at official stations, particulars of some other types are included to illustrate different principles. Where these other types are not described in detail, sources of fuller information are given. It is hoped that the book will also be helpful to users of meteorological instruments outside the Meteorological Office. These readers should, however, understand that certain instructions on procedures are for the guidance of Meteorological Office personnel.

In addition to giving, where applicable, instructions for the installation, operation, and maintenance of Meteorological Office pattern instruments, this handbook deals with accuracy and sources of error.

The general requirements of meteorological instruments, both indicating and recording, are:

(a) Accuracy
(b) Reliability
(c) Ease of reading and manipulation
(d) Robustness and durability
(e) Low cost of ownership.

Most meteorological instruments have to be maintained in continuous operation and many are partially or wholly exposed to the weather. These restrictions call for especially high standards of design and manufacture. The need for uniformity is one of the most important requirements for meteorological measurements. The decisions and recommendations of the World Meteorological Organization, which affect instrument practice, have therefore been followed as closely as possible.

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VOLUME 5

MEASUREMENT OF PRECIPITATION AND EVAPORATION

1 PRECIPITATION — GENERAL

1.1 Purpose of measurement

Precipitation falls on the surface of the earth in the form of rain, snow, sleet, drizzle and hail. The purpose of precipitation measurement is to obtain as much information as possible about the amount and distribution, in time and space, of this precipitation. The simplest and most usual way of doing this is to set up gauges with a horizontal circular aperture of known diameter, and to collect and measure at regular intervals the precipitation which falls through the aperture. It is assumed that the amount collected per unit area of the aperture of the gauge is the same as the amount per unit area, falling on the surrounding surface.

Surface condensation phenomena such as dew, fog, hoar frost and rime can contribute to the catch of a rain-gauge and are regarded as precipitation for the purpose of this volume.

There are probably few areas of any size which have a denser network of gauges than one to every 25 km^2, so that, with a gauge diameter of 5 inches, the area from which water is actually collected and measured is under one thousand millionth part of the area of which the point measurement is taken to be representative. In most areas of the world the fraction is much smaller. In spite of the smallness of this fraction the rainfall over an area around a gauge is assumed to be equal to the point rainfall measured by the gauge, so it is necessary to ensure that the exposure of the gauge is such that local sources of error are reduced as much as possible.

1.2 Units of measurement

Precipitation is measured as the depth to which a flat horizontal impermeable surface would have been covered if no water were lost by run-off, evaporation or percolation. A measurement is made of the total precipitation, whether of rain, hail or snow, in the form of the equivalent depth of liquid water, i.e. any snow or hail is melted and added to any rain that has already fallen. In addition, in heavy falls of snow, a measurement is taken of the total depth of snow. As a first approximation 300 mm of snow can be taken to give 25 mm of liquid water, and this can be used as a check on the readings recorded in the gauge itself by melting the snow collected. The details of the methods to be used in this case are dealt with more fully in the *Observer's Handbook*.

The units of depth in current use in the British Isles are millimetres and inches. In the Meteorological Office all observations are made in millimetres but some other observers use inches.

1.3 Effect of exposure and selection of site

The measurable amount of rain collected in a rain-gauge is generally less than the actual rainfall at the rain-gauge site. This effect arises from various causes such as evaporation, adhesion of rain to the rain-gauge and collecting bottle 'out-splash', but by far the greatest factor is that due to the exposure of the rain-gauge to the wind which, as shown in Table I, generally causes a larger error than all the other causes combined (Rodda 1971).

Table I. *Approximate errors in precipitation measurement* (after Kurtyka)

Evaporation	Adhesion	Colour	Inclination	Splash	Total
		per cent			
−1.0	−0.5	−0.5	−0.5	+1.0	−1.5
		Exposure −5 to −80 per cent			

The variation caused by the wind is mainly due to the acceleration of the ambient airflow as it moves in a nearly horizontal plane across the mouth of the gauge. The effect of the acceleration is to increase the distance between the falling drops compared to their distance apart several feet above the gauge, with the result that some drops are lost. The magnitude of the effect is roughly proportional to the horizontal gradient of wind speed $\frac{\partial u}{\partial x}$ and thus to u, the horizontal wind speed, just above the gauge. However, the larger the droplets the greater, generally, is their vertical velocity which decreases the effect of the local acceleration $\frac{\partial u}{\partial x}$. The effect of eddies would be particularly marked if they reduced the net vertical velocity of the drops, e.g. if the wind is blowing upslope locally around the gauge. It is important that the observations at different stations should be comparable, and thus that the instrument exposures should be similar. With this object in mind the site of a rain-gauge should be chosen so that the horizontal wind speed across the gauge is a minimum and that eddies locally around the gauge, especially those with a marked upward vector, are reduced without at the same time increasing or decreasing the catch due to the direct influence of surrounding objects.

The gauge should be on level ground, not upon a slope or terrace and certainly not on a wall or roof. It should on no account be placed where the ground falls away steeply on the side from which the prevailing wind blows. Its distance away from every surrounding object must be not less than twice the height of the object above the rim of the gauge and normally at least four times. Provided these conditions are satisfied a position as sheltered from the wind as possible is preferable to an exposed one, especially at mountain, moorland or coastal stations. At these stations great care should be taken to avoid overexposing the gauge to the sweep of the wind.

When it is impossible to secure an exposure with some natural shelter it is often desirable, after selecting the most suitable site, to build a turf wall around the gauge. The recommended wall (Figure 1) has an inside diameter of 3 m with its crest horizontal and in the same plane as the rim of the gauge. The inside of the wall should be vertical and the outside of the wall sloping down gradually, preferably by about 1 in 4, and its crest should be about 150 mm thick. The inside of the wall should be supported by wooden palings driven into the ground with their tips level with the rim of the gauge and the crest of the wall. The palings serve a dual purpose by preventing the collapse of the inner, vertical, wall and by acting as a guide to which the crest of the wall should be maintained. A drain-pipe should be installed to drain off the water which collects inside the turf wall.

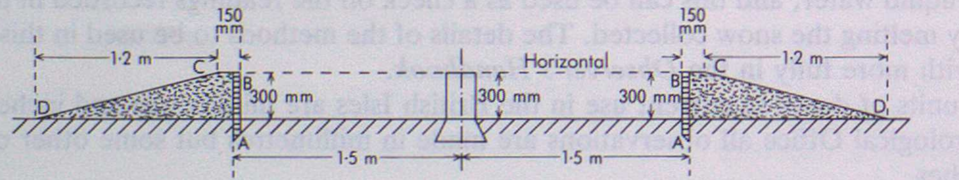


Figure 1. Turf wall for use at exposed rain-gauge sites.

The loss of catch in very open situations, such as those which require a turf wall, are due to the effect of the gauge obstructing the airflow and causing local accelerations, as explained previously. It is possible to mount a gauge with its rim flush with the ground so that the horizontal wind across the gauge, and thus $\frac{\partial u}{\partial x}$, is reduced. Such a gauge, however, needs to be surrounded by an anti-splash grid (see below) and is prone to flooding. A large proportion of gauges are mounted with their rims at a standard height above the ground. For non-recording rain-gauges the standard height is 300 mm ± 20 mm but for recording rain-gauges the height is usually greater and depends upon the type of rain-gauge.

A method of reducing 'in-splash' is that suggested by Bleasdale (1959). This is an array of thin metal slats, as used in venetian blinds, fixed to radial bars projecting from just beyond the rim of the rain-gauge out to a distance of 610 mm. The slats are inclined at 45° to the horizontal and are so placed that splashes will tend to be directed away from the rain-gauge. Below the slats is a gravel bed so that when the rain runs off the slats it drains away.

The height above mean sea level of the ground upon which the rain-gauge stands is used as the height of the station, and should be determined to the nearest metre surveying with reference to a local bench mark if possible. The approximate height may be easily ascertained in most cases by reference to Ordnance Survey maps.

2 NON-RECORDING RAIN-GAUGES

Non-recording rain-gauges may be divided into two main classes, those which are read at daily intervals and those which are read only at intervals of a week or a month.

Despite the increasing use of SI units, the dimensions of older, established designs of rain-gauges in the British Isles are still referred to in their original imperial units. Where applicable therefore imperial units are retained.

2.1 Rain-gauges for daily readings

Meteorological Office rain-gauge Mk 2. The Meteorological Office rain-gauge Mk 2 (Figure 2(a)) consists of:

(a) An upper section which is a cylindrical portion with an accurately turned and bevelled rim, within which is attached a funnel.
(b) An outer case with a splayed base.
(c) A cylindrical collecting can fitted with a wire handle.

The upper section fits closely on top of the outer case, the tube of the funnel fitting inside a glass bottle placed in the collecting can. The upper section and collecting can are made from seamless drawn copper tubing, but the remainder of the gauge, apart from the brass fittings and the bottle, is made from sheet copper with soldered seams. The use of copper tubing in the construction of the cylindrical portion ensures the interchangeability of the funnels among different gauges. The brass rim has a mean diameter of 5 inches, and the cylindrical portion is over 4 inches deep to minimize the amount of rain lost by out-splashing from the sides of the funnel and to hold a reasonable quantity of snow or hail. The rain is collected in the glass bottle or exceptionally it may flow into the collecting can. On rare occasions the collecting can may become filled as well and the water will overflow into the outer case. When this occurs the outer case has to be dug up and the water transferred to a suitable vessel before it is measured.

Installation. The gauge should be set in the ground, or in an earthenware drain-pipe fixed in the ground, and fixed firmly so that it will not be blown over or tilted by the strongest winds. The conventional surrounding surface is short grass, but if this is not possible the gauge may be set up in gravel or the like. A hard smooth surface such as concrete should be avoided because of the increased risk of rain splashing into the gauge. The soil should be pressed firmly around the outer case but not rammed down excessively, as there is otherwise a risk of splitting the seams. The rim of the gauge should be 300 mm ± 20 mm above the surrounding ground and set horizontally, checking with a spirit-level across the top in two directions at right-angles.

Maintenance. A careful watch should be kept for cracks in the bottle and a cracked bottle should be replaced immediately. The bottle should be washed out occasionally and thoroughly dried.

The gauge should be tested occasionally at each seam for leaks, especially after any spell of severe frost. The funnel and collecting can should be tested by filling them with water, and observing that the water does not escape at any point. When testing the funnel in this way it will, of course, be necessary to close the lower end of the delivery pipe by means of the finger. Alternatively the funnel may be tested by closing the lower end of the delivery tube, inverting the funnel and pressing it vertically downwards into a bucket of water. The presence of a leak will be shown by the escape of air bubbles.

Testing the outer case *in situ* by filling with water is not very practical. Therefore, as long as the interior of the outer case is dry, it is usual to assume that there are no leaks. If, however, water is present inside the outer case, and the funnel and collecting can are known to be watertight, it will be necessary to remove the outer case from the ground for testing.

The height and level of the rain-gauge rim should be checked from time to time and corrected if necessary.

The funnel should be kept clear of leaves and other debris which might block the delivery tube and prevent collected water from flowing into the bottle.

2.2 Rain-gauges for weekly and monthly readings

These rain-gauges are for use at isolated localities where readings can only be taken at weekly or monthly intervals. The main differences between these rain-gauges and the daily type just described are their larger capacity and stronger construction.

The general instructions for installation and maintenance of monthly rain-gauges are the same as those for the daily type.

Octapent rain-gauges Mk 2A and Mk 2B. The Octapent rain-gauge Mk 2A (Figure 2(b)) consists of the funnel, with the usual accurately turned and bevelled 5-inch diameter brass rim, which fits on top of the outer case consisting of a cylindrical portion soldered to a splayed base. Inside the outer case is an inner collecting can which has a narrow opening at the top for the entry of the funnel tube, and a larger circular opening to one side of the funnel entry for the insertion of a 'frost protector' (see below). The collecting can is provided with a handle at the top and also a pair of handles at the side to assist in pouring out the water. These handles fold closely to the sides of the collecting can when it is inserted in the outer case. The collecting can is made from seamless drawn copper tubing of uniform diameter. The inner can should always be carefully handled to avoid any dents which may impair the accuracy of the measurements which are made with a dip-rod (see page 5-7). As with the Meteorological Office rain-gauge Mk 2 the use of copper tubing for the cylindrical parts of the Octapent rain-gauge ensures interchangeability.

The Mk 2B Octapent rain-gauge is similar to the Mk 2A version except that it has a longer central cylindrical portion and a correspondingly longer collecting can giving it a capacity of 1270 mm of rain as opposed to the 680 mm of the Mk 2A. The Mk 2B rain-gauge is intended for use in regions of high rainfall, and where the rain-gauge may have to be left occasionally for as long as two months or more without a visit.

The frost protector consists of a length of stout rubber hose weighted and closed at the lower end with a piece of lead. The hose is just long enough to come to the top of the collecting can when placed upright in the can. The protector operates by collapsing slightly under the pressure due to the expansion of the water when it freezes, and thus relieves the walls of the collecting can from excessive pressure. Care should be taken when inserting the protector not to drop it violently on to the base of the collecting can. The protector should be removed before a measurement is made with a dip-rod (see page 5-7).

Bradford rain-gauge Mk 4. The Bradford rain-gauge Mk 4 (Figure 2(c)) has a 5-inch diameter aperture and is constructed mainly of copper. The collecting can, the cylindrical portion of the funnel and, in some instruments, the outer case are made of seamless copper tubing. To minimize evaporation the collecting can is fitted with a diaphragm at the top

which is perforated only (a) for the admission of the funnel tubing and the dip-rod and (b) at one side to pour out the water. The dip-rod and funnel are interchangeable among different gauges.

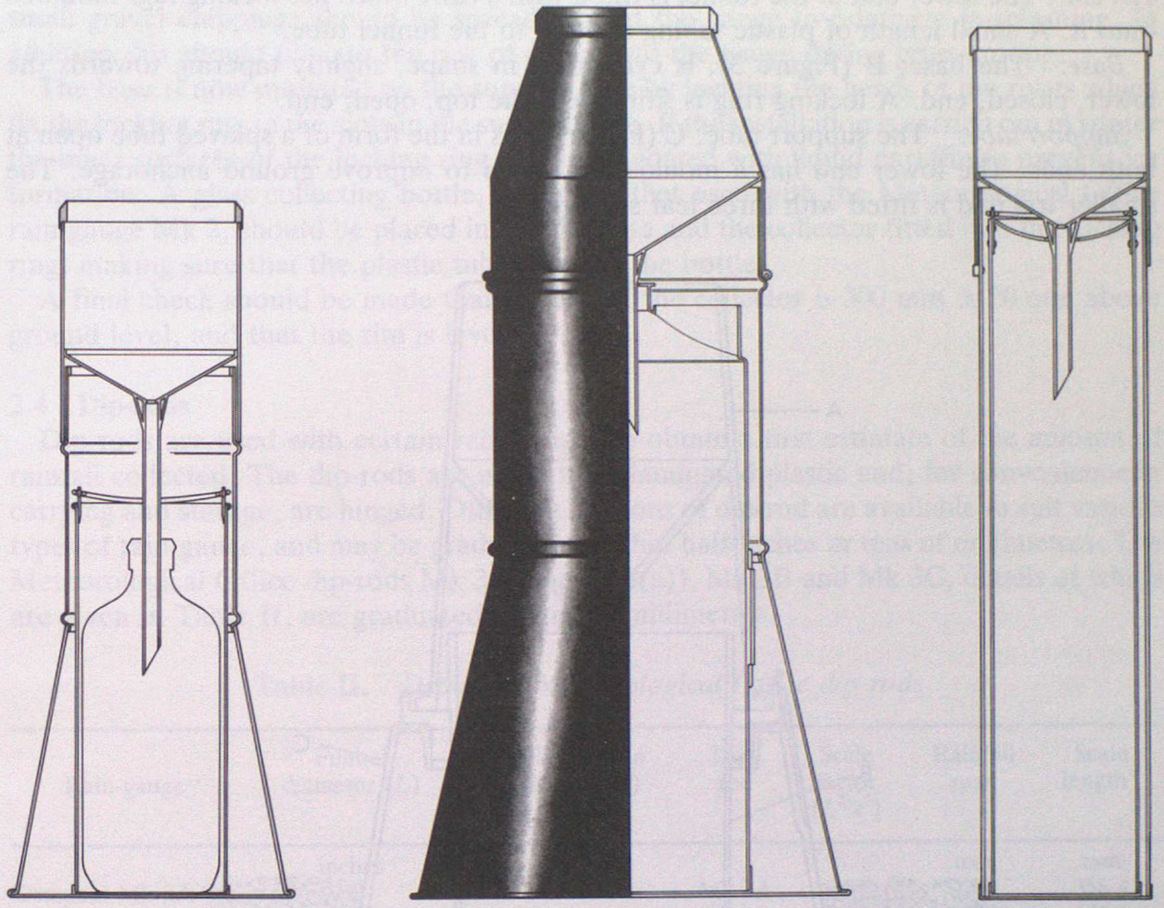


Figure 2. Rain-gauges for daily and monthly readings.
(a) Meteorological Office rain-gauge Mk 2
(b) Octapent rain-gauge Mk 2A
(c) Bradford rain-gauge Mk 4

2.3 Meteorological Office Mk 3 rain-gauge system

The Meteorological Office Mk 3 rain-gauge system is designed to allow flexibility in the methods of measuring, transmitting and recording rainfall amounts. This flexibility is achieved by having a range of interchangeable components for the basic gauge, together with various 'add-on' components.

The main material used in the construction of the basic components of the rain-gauge system is glass-reinforced polyester resin. This material is chosen because of its low thermal conductivity and freedom from corrosion or electrolytic problems. As the parts are made in moulds it follows that all parts from the same mould will be virtually identical, thus ensuring interchangeability.

Certain of these basic components can be combined to form a standard total gauge, or, if fitted with a tipping bucket switch, to provide an output suitable for indicating, recording or telemetering rainfall amounts on appropriate equipment (see page 5-21).

Component parts of the standard total rain-gauge Mk 3

150 cm² collector. The collector, A (Figure 3), is in the form of a funnel. A ring fitted to the rim of the funnel has an internal diameter of 138.2 mm providing a collecting area of 150 cm^2. The lower end of the funnel is fitted with a skirt which has locking lugs moulded onto it. A small length of plastic tubing is fitted to the funnel tube.

Base. The base, B (Figure 3), is cylindrical in shape, slightly tapering towards the lower, closed, end. A locking ring is fitted near the top, open, end.

Support tube. The support tube, C (Figure 3), is in the form of a splayed tube open at both ends. The lower end has a moulded-in flange to improve ground anchorage. The smaller top end is fitted with three leaf springs.

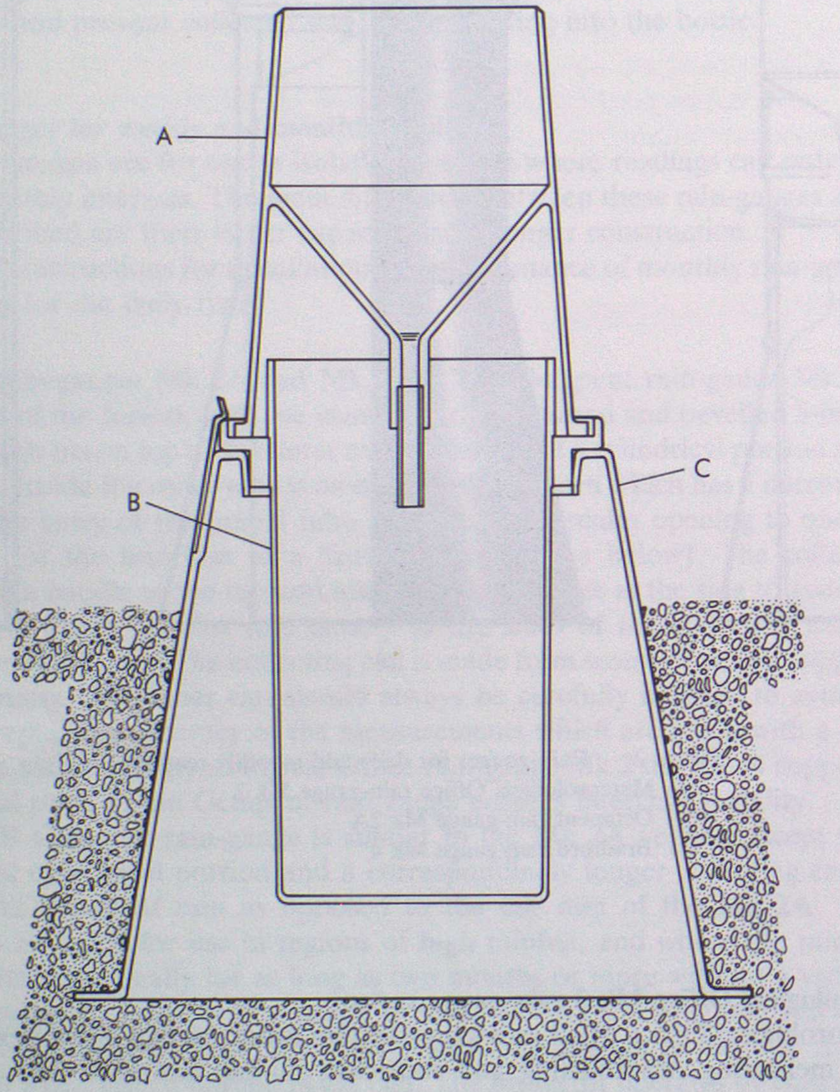


Figure 3. Meteorological Office Mk 3 rain-gauge.

Installation. Before commencing the installation, a pencil or chalk ring should be marked round the circumference of the support tube at a distance of 240 mm from the flange. This is the level to which the tube will be buried.

A hole about 500 mm deep and 450 mm diameter should be dug and the bottom of the hole filled with gravel or clinker to a depth of about 250 mm. The support tube should now be placed in the hole and the amount of gravel adjusted until the chalk line previously marked round the support tube is at ground level and the top of the support tube is horizontal, checking with a spirit-level across the top in two directions at right-angles. The support tube should now be firmly anchored by placing at least four bricks or heavy stones on the flange, and the height and level again checked. The hole around the outside of the support tube should then be filled with more gravel or clinker making sure that it is well packed down around the flange of the support tube. Finally a ring, about 150 mm wide, of small gravel chippings should be spread around the gauge to minimize in-splashing. In addition this should obviate the risk of damage to the gauge during grass cutting.

The base is now mounted on the support tube by locating the heads of the rivets which fix the locking ring in the slots in the support tube. If the installation is carried out in winter the inner surfaces of the locking ring should be coated with liquid paraffin to prevent ice formation. A glass collecting bottle, similar to that used with the Meteorological Office rain-gauge Mk 2, should be placed inside the base and the collector fitted into the locking ring, making sure that the plastic tubing enters the bottle.

A final check should be made that the rim of the collector is 300 mm ± 20 mm above ground level, and that the rim is level.

2.4 Dip-rods

Dip-rods are used with certain rain-gauges to obtain a first estimate of the amount of rainfall collected. The dip-rods are made from laminated plastic and, for convenience in carrying and storage, are hinged. Different versions of dip-rod are available to suit various types of rain-gauge, and may be graduated in either half-inches or tens of millimetres. The Meteorological Office dip-rods Mk 3A (Figure 4(a)), Mk 3B and Mk 3C, details of which are given in Table II, are graduated in tens of millimetres.

Table II. *Details of Meteorological Office dip-rods*

Rain-gauge	Funnel diameter (L)	Collector can diameter (e)	Dip-rod	Scale factor (L^2/e^2)	Rainfall span	Scale length*
	inches	inches			mm	mm
Octapent Mk 2A	5	7	Mk 3A	0.51	700	358.4
Octapent Mk 2B	5	7	Mk 3B	0.51	1280	655.1
Bradford Mk 4	5	4.5	Mk 3C	1.23	380	472.7

* The scale length takes into account the volume of water displaced by the dip-rod.

When measuring the rain the dip-rod is inserted into the collecting can until the metal tip of the dip-rod touches the base of the can. The rod is then withdrawn and the amount of rain is given by the length of rod which is damp. The amount of rain as measured by the dip-rod should be noted, and then the water should be measured accurately by means of a rain measure (see page 5-8). When not in use the dip-rod should be stored in a dry place.

2.5 Rain measures

The amount of rain collected by a gauge is measured with the aid of glass vessels known as rain measures. They are graduated to indicate directly the amount of rain which has fallen, and are available in a variety of sizes depending on the diameter of the aperture of the gauge with which they are being used, and whether it is a monthly or daily gauge. Rain measures can be obtained with graduations figured in millimetres or in inches of rainfall.

Rain measures can be classified broadly into tapered (Figure 4(b)) and flat-based (Figure 4 (c)) models. Both have a main cylindrical body, but the tapered model decreases in diameter in the lower part and is rounded-off at the base, while the flat-based models have a flat horizontal base with a flange, so that they can be stood in an upright position on a horizontal surface. The Camden model, designed originally for the British Rainfall Organization, has a flat horizontal base and a vertical cylindrical outer surface, but the

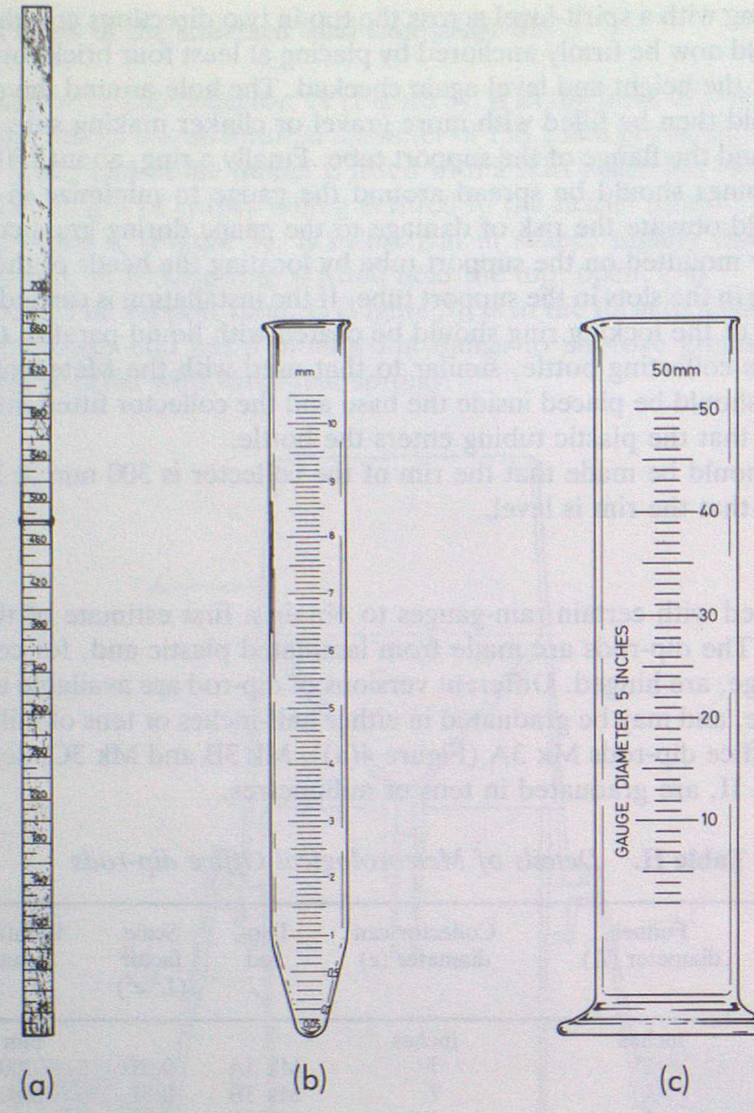


Figure 4. Dip-rod Mk 3A and rain measures.
(a) Dip-rod
(b) Tapered rain measure
(c) Flat-based rain measure

inner surface, while being a vertical cylinder at the top, tapers at the base in a similar manner to the tapered models.

The flat-based models, with the exception of the Camden rain measure, are not recommended for routine use, as they are not sufficiently accurate for measuring small amounts of rain.

The Meteorological Office rain measures for use with the Mk 2 and Mk 3 rain-gauges are graduated in millimetres with graduation marks every 0.1 mm and with an additional graduation mark for 0.05 mm. Figuring is at 0.1 mm, 0.5 mm and every 1 mm from 1 mm to 10 mm. The maximum errors allowed in the rain-measure graduations are ± 0.05 mm of rainfall at or above the 2 mm graduation mark and ± 0.02 mm of rainfall below the 2 mm graduation mark.

In the following guide to the use of rain measures, the appropriate measurements for rain measures graduated in inches of rainfall are included in brackets for comparison.

When the amount of water is equivalent to 0.05 mm (0.005 in) or above, the measurement is recorded to the nearest 0.1 mm (0.01 in), but a special record of a 'trace' is made whenever either of the two following conditions hold:

(a) When there is less than 0.05 mm (0.005 in) of rain in the gauge and the observer knows that this is not the result of a drop or two of water draining from the sides of the can or bottle after emptying out the rainfall at the preceding observation, i.e. the observer must be reasonably sure that there has actually been precipitation since the preceding measurement. If the precipitation has been in the form of dew or wet fog this should be noted.

(b) When no water is observed in the gauge but when the observer knows from his own observation that some rain or other precipitation (snow, hail or sleet) has fallen since the last observation. This sometimes happens, especially in warm dry weather, without the gauge being even damp, because the water has evaporated before it reached the collecting can. It is to assist in distinguishing between a trace and 0.1 mm (0.01 in) that the taper and Camden measures have a graduation mark at 0.05 mm (0.005 in). The reading of 0.05 mm (0.005 in) should never be recorded; only a trace or 0.1 mm (0.01 in).

When reading the amount of rainfall the measure should be held vertically; the flat-based measures may be placed on a horizontal surface. The eye should then be brought to the same level as the water meniscus and the reading of the bottom of the meniscus taken to the nearest 0.1 mm (0.01 in). Figure 5 shows various amounts of rain in rain measures and the correct reading that should be made from them.

If the water collected in the gauge exceeds the capacity of the measure, the measure should be nearly filled to the top mark, the reading taken, and the contents poured into a container. This should be repeated as often as necessary and the readings then totalled. The reading can then be checked by re-measuring the contents of the container. It should always be remembered that rain measures are fragile, and they should be treated carefully at all times, kept clean, and stored in a safe place when not in use, preferably inverted.

In cold weather it is advisable to store the rain measure indoors when not in use.

2.6 Accuracy required

The amount of the total precipitation is measured to the nearest 0.1 mm or 0.01 in, and the depth of snow to the nearest whole millimetre or 0.1 in.

The accuracy with which the catch of the rain-gauge represents the amount of rain which has fallen in its vicinity depends on:

(a) The several factors which may be summed up as due to the 'exposure of the gauge' which were discussed earlier.

(b) The accuracy of the constituent parts of the instrumentation, e.g. the accuracy of the rain measure, how close the aperture of the rain-gauge is to its nominal diameter, and the accuracy of the dip-rods and collecting can combined.

(c) The accuracy with which the rain-gauge is levelled.

The Meteorological Office Mk 2, Octapent and Bradford rain-gauges have a maximum permissible error of 0.01 in in the mean of any four equally spaced diameters of the aperture of the rain-gauge, with a tolerance of ±0.02 in in any one diameter. This is equivalent to a possible error of ±0.4 per cent in the area of the aperture. The corresponding values for the Mk 3 150 cm^2 collector are ±0.25 mm and 0.35 per cent.

The maximum permissible errors for Meteorological Office rain measures are given on page 5-8.

In the Octapent rain-gauges the uncertainty in the diameter of the collecting can leads to a possible error of ±0.3 per cent in the cross-sectional area, whilst the dip-rods themselves have a maximum permissible graduation error of ±1 mm of rainfall. In the Bradford rain-gauge the corresponding values are ±0.4 per cent and ±0.5 mm.

The combined uncertainties of the instrumentation (funnel aperture, collecting can, rain measure and dip-rod) is well within the uncertainty caused by the varying exposures of different gauges and the losses due to the measurement technique (pouring from one vessel to another).

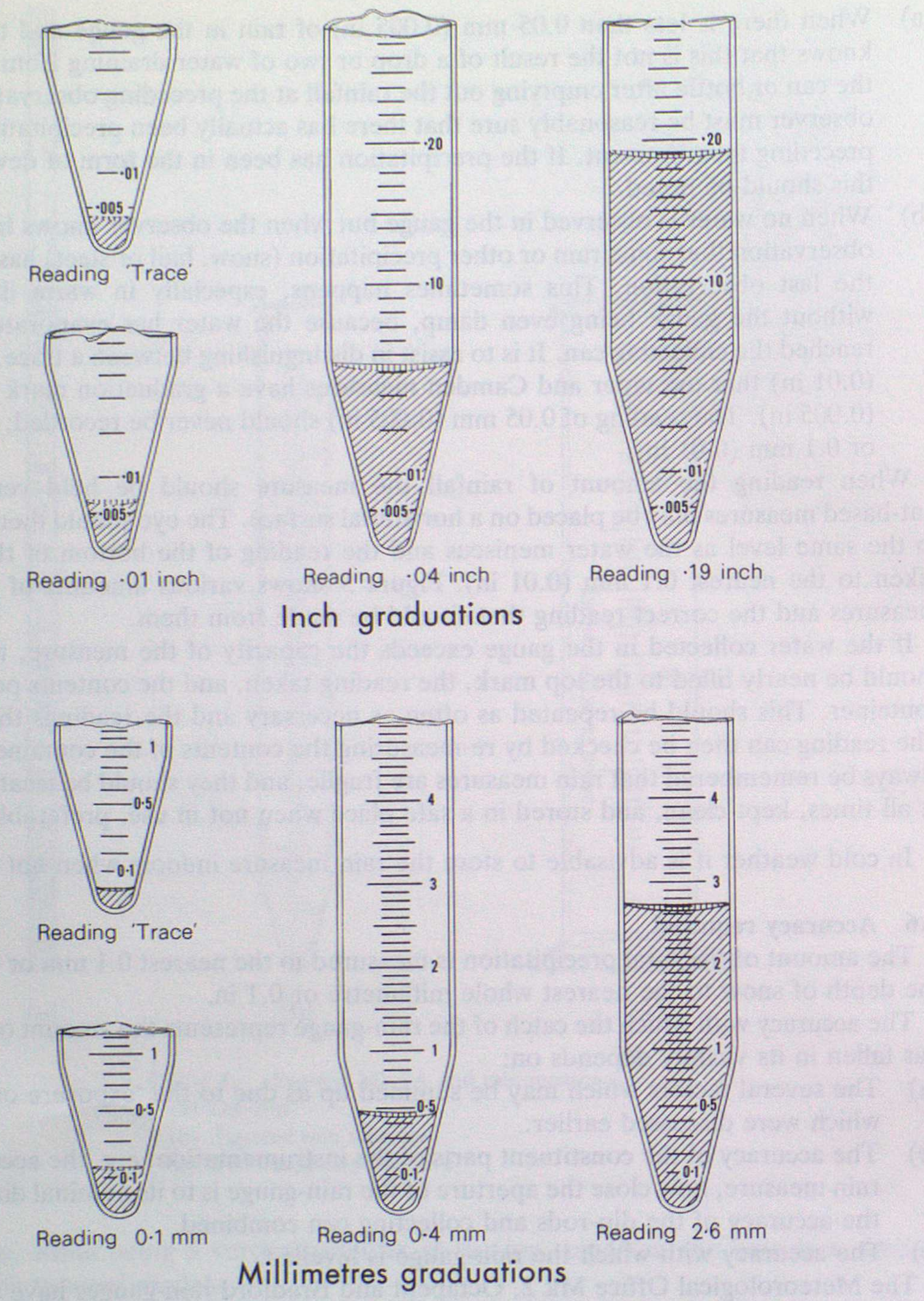


Figure 5. Reading the rain measure
The reading 'trace' is also applicable when rain is known to have fallen, even if the gauge is dry.

3 RECORDING RAIN-GAUGES

Recording rain-gauges are used to keep a continuous record of the rainfall. They may be divided roughly into two main classes:

(a) Those which record the total amount of rainfall which has fallen since the record was started.
(b) Those which record the rate of rainfall either directly as a rate or in small increments of total rainfall amount.

The rate of rainfall at any given time may be determined from the first class of instrument, with varying accuracy according to the instrument used, by measuring the amount of rain which has fallen in a short period centred about the given time. It is not as easy to determine the amount of rain which has fallen in any time by the use of a rate-of-rainfall recorder.

The main use of recording rain-gauges is the determination of the times of onset and cessation of rain and the varying rate of rainfall during those periods. It is usual to have an ordinary rain-gauge exposed close by for use as a standard by which the readings can be checked and if necessary adjusted.

Rain recorders of the first class mentioned above can be classified into three main types:

(a) Float gauges with automatic siphoning arrangements.
(b) Tipping-bucket gauges.
(c) Weight gauges.

Float rain-gauges record the movement of a light float in a float chamber into which the rain is led. In general these rain-gauges suffer from the disadvantage that once the float chamber is filled the record must cease or some means must be provided for emptying the float chamber. The usual result is that some rainfall is inevitably not recorded. Tilting-siphon types are preferable to natural-siphon types as they lose less record as the siphoning is quicker. On the other hand the natural-siphon gauge is simpler and cheaper to construct.

The tipping-bucket gauge does not keep a strictly continuous record of rainfall, but instead records rainfall increments. Each increment is equivalent to the amount of rainfall required to tip the bucket mechanism. In tipping-bucket rain-gauges the water surfaces exposed to the air are large, compared with those in float rain-gauges, so that errors due to evaporation in light or intermittent rain may be significant. Another disadvantage is that the tipping motion takes a finite time, and that for the first half of that time rain is still being led into the full compartment. Against these disadvantages must be placed the general reliability of the instrument and its ability to record at a distance.

The weight gauge operates by recording the total weight of precipation in the collecting can. The collecting can usually descends against the compression of a spring or the displacement of a weight. A weight gauge can be made sufficiently accurate for use as a reference standard (see page A-13).

3.1 Meteorological Office tilting-siphon rain recorder Mk 2

In the Meteorological Office tilting-siphon rain recorder Mk 2 (Figure 6) water collected in a circular funnel is led into a cylindrical vessel containing a float moulded from polyurethane foam. The vertical motion of this float, as the water level rises, is communicated by means of a float rod to a pen which records on a chart on a revolving drum. The details of the design are mainly concerned with the method of emptying the cylindrical float chamber after it has been filled with water and so keeping the record continuous.

The recording mechanism is set up inside the container which consists of three main parts, namely the funnel assembly, the base casting and the base itself. The funnel has an aperture fitted with a turned brass rim of 287.27 mm internal diameter. A hinged clear acrylic window, capable of being locked by means of a hasp, staple and padlock, is fitted in the lower half to give access to the pen and recording chart when the instrument is in use. The whole funnel assembly is hinged on to the base casting and carries a hasp which can be engaged with a staple on the base casting and padlocked if desired.

The base casting supports the recording mechanism and consists of a circular gun-metal casting flanged to take the funnel and the base. The base itself is splayed and made of copper sheet, forming a support for the whole instrument. The float chamber, clock and drum, the trigger catch and the pen-lifter rod are mounted on a special sub-base plate which is screwed on to the main base casting. By means of the screws the sub-base can be accurately levelled independently of the main instrument.

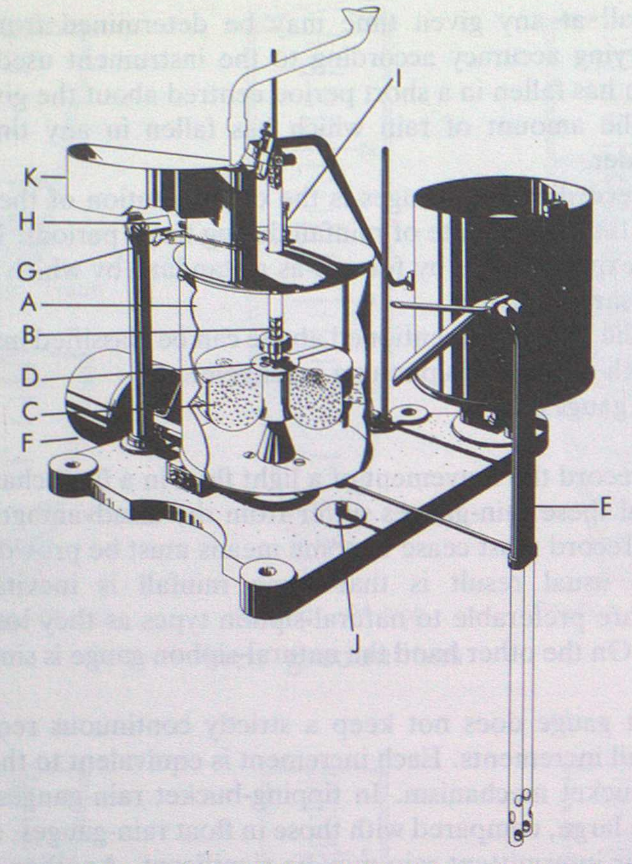


Figure 6. Meteorological Office tilting-siphon rain recorder Mk 2.

After collection the water is led into the main float chamber A via a wire-gauze filter and a small opening in the top of the chamber. The float rod B moves up and down between two bearings, one in the top and one in the base of the float chamber. To prevent the float C from turning about its axis a guide, D, attached to the top of the float, engages loosely with a projection formed up the side of the float chamber.

To the side of the float chamber are attached the siphoning tubes E arranged so that the tops of the bend in the tubes are level with the top of the float chamber. The whole float chamber is mounted on knife-edges and is counterbalanced by the weight F so that when the chamber is empty or only contains up to the equivalent of 4 mm of rain the system rests on the knife-edge and a back stop. With more than 4 mm of rain and up to the maximum of 5 mm the weight is insufficient to hold the chamber on the back stop but the chamber is prevented from overbalancing by means of trigger G which engages with the trigger catch H. When the 5 mm of rain have been collected a stop on the top of the float pushes against the screw at the other end of the trigger to the trigger catch, and releases the trigger from the catch. The float chamber then tilts over until stopped by the front stop J, the water flows over the tops of the bend in the siphon tubes and a siphoning action is started. Water flows out of the float chamber until the level falls to the top of the exit hole of the float chamber when the siphoning action ceases. In the meantime, when the total weight of the float chamber and contents has decreased sufficiently, the system resumes its vertical position, the whole assembly resting again on the knife-edge and the back stop ready for the process to be repeated.

To reduce the loss of rain during the siphoning process, a rain-trap K, consisting of a nearly semi-circular bowl is attached to the filter housing. During siphoning any rain entering the funnel collects in the rain-trap at the end nearest the filter housing. The base of the rain-trap slopes downwards away from the filter housing, so that when the system resumes an upright position any water in the rain-trap flows to the opposite end, where it passes through a drain into the float chamber.

The pen arm is attached to the float rod by means of a gate suspension (see page A–4). At the moment of siphoning the pen arm is lifted from the chart by the pen-lifter rod, and it does not come into contact with the chart again until the float chamber resumes its vertical position. This happens before the siphoning is completed so that the pen returns to the chart above the zero line as siphoning finishes.

The clock is the Meteorological Office standard Mk 2B with an 'S' drum (see page A–6), and is mounted slightly higher than the float chamber. The relative positions of the float chamber and clock and drum are shown in Figure 7. In addition to its function of lifting the pen from the drum when siphoning occurs the pen-lifter rod is used for removing the pen from the chart when changing the chart daily. This is done by moving the lever attached to the base of the pen-lifter rod. If it is to continue to perform the first function properly the pen-lifter rod must not be set very far back from the pen arm.

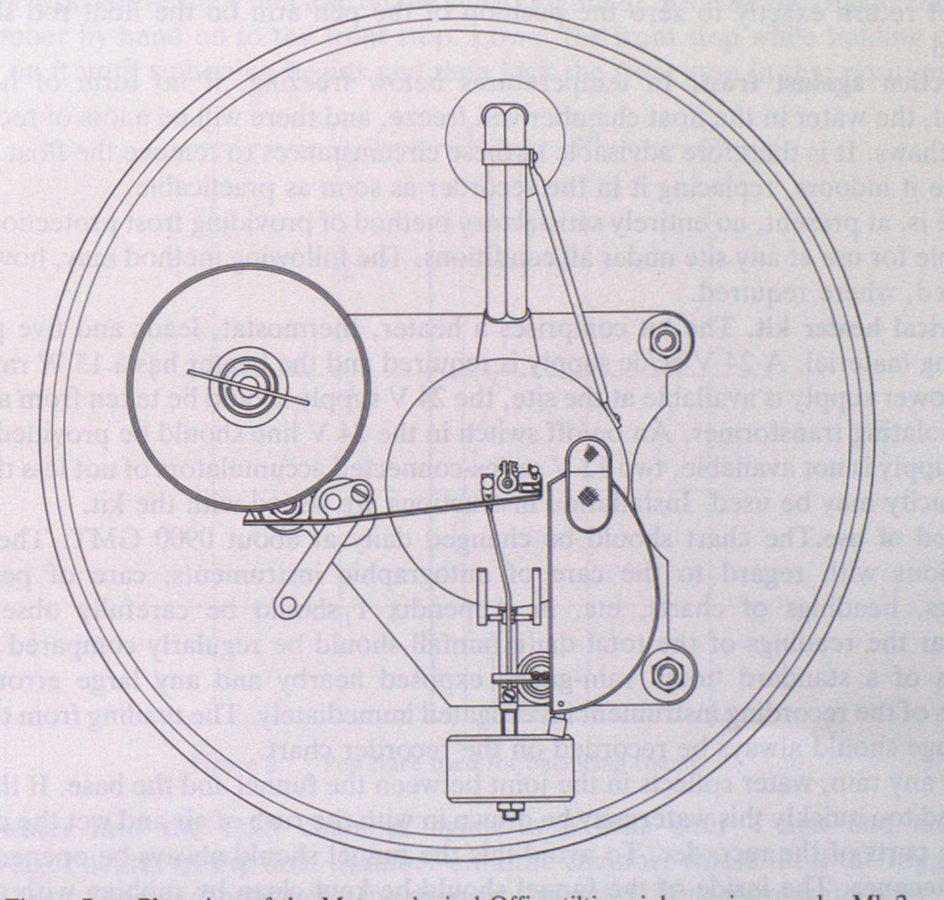


Figure 7. Plan view of the Meteorological Office tilting-siphon rain recorder Mk 2.

Installation and adjustment. A hole should be dug approximately 500 mm deep and 600 mm in diameter and the bottom covered with a layer of rubble for drainage. Two or three large pieces of concrete slab bedded horizontally in the rubble around the circumference will help to prevent the recorder from tilting due to any subsidence.

If the water table rises to within about 100 mm of the surface of the ground, the bottom of the siphon tube may dip into water thus preventing the recorder from functioning properly. This may happen on occasions of very heavy rainfall and can only be completely prevented by expensive piped drainage. The trouble may, however, be avoided, except on the most troublesome sites on occasions of exceptional rainfall, by installing the recorder on the edges of two concrete slabs set in a deep bed of porous rubble.

The recorder should be lowered carefully into the prepared hole, a check being made that the top of the splayed base is level with the surrounding ground and that the rim is horizontal and 535 mm above the ground level. The hole around the base should then be filled in with soil, pressing the soil down firmly, and the soil covered with turf to give a level grass surface up to the recorder. If the site is ungrassed, a ring of gravel chippings should be spread around the recorder.

The funnel support should be pushed into the ground in a suitable position to support the hinged top of the recorder just below the brass rim.

A clock, drum and chart may now be fitted to the recorder. The pen should be filled with ink and the drum rotated by hand to check that the trace is parallel to the horizontal lines on the chart.

Each rain recorder is adjusted by the Instrument Branch Test Laboratory prior to issue. When installing the recorder therefore, the only adjustment that may be necessary is in the zero reading. This is accomplished by pouring water into the float chamber until siphoning takes place. When the float chamber returns to the vertical the pen should return to the chart well above the zero line and then fall to the zero line as siphoning finishes. If the pen does not return exactly to zero the position of the pen arm on the float rod should be adjusted.

Protection against frost. In temperatures below freezing, if no form of heating is installed, the water in the float chamber will freeze, and there will be a loss of record until the ice thaws. It is therefore advisable in these circumstances to remove the float chamber and take it indoors, replacing it in the recorder as soon as practicable.

There is, at present, no entirely satisfactory method of providing frost protection* which is suitable for use at any site under all conditions. The following method may, however, be employed, where required.

Electrical heater kit. The kit comprises a heater, thermostat, leads and five pieces of insulating material. A 24 V ac/dc supply is required and the heater has a 15 W rating. If a mains power supply is available at the site, the 24 V supply should be taken from a suitable mains isolating transformer. An on/off switch in the 24 V line should be provided. Where mains supply is not available, two 12 V series-connected accumulators of not less than 60 A h^{-1} capacity may be used. Installation instructions are issued with the kit.

Method of use. The chart should be changed daily at about 0900 GMT. The general instructions with regard to the care of autographic instruments, care of pens, time markings, headings of charts, etc. in Appendix 1 should be carefully observed. In particular the readings of the total daily rainfall should be regularly compared with the readings of a standard 'total' rain-gauge exposed nearby and any large errors in the readings of the recording instrument investigated immediately. The reading from the 'total' rain-gauge should always be recorded on the recorder chart.

After any rain, water collects in the joint between the funnel and the base. If the funnel is opened too quickly this water may be drawn in with the rush of air and wet the chart and working parts of the recorder. To avoid this the funnel should always be opened gently.

Maintenance. The inside of the funnel should be kept clean by rubbing with a dry rag (polish should not be used) and the hinge oiled occasionally. The rain-trap should be removed periodically and inspected and cleaned. If the small hole in the rain-trap leading to the drain becomes blocked, the small rubber cap on the end of the drain tube should be removed and the hole cleaned out with a piece of wire. A light smear of silicone grease applied very occasionally to the inside of the rain-trap will improve the run off. The filter should be cleaned with methylated spirit.

The instrument should be tested occasionally, especially when no rain has fallen for some time. This can be accomplished by pouring into the funnel measured quantities of water corresponding to a specific interval on the chart. This is most easily done by using a millimetre measure for a Mk 2 rain-gauge. If 5.1 mm of water in the measure is poured into the funnel the pen should indicate 1 mm on the chart.

* In the past, if mains power was unavailable and the use of accumulators was inconvenient, a simple, cheap method of protection against frost was the use of night-lights. Night-lights of suitable specification for this use are no longer available and the use of candles is not recommended.

The time of siphoning should be checked occasionally in case the outlet tubes are becoming blocked. The siphoning time should be approximately 8 seconds. The drain filter through which water from the siphon tubes passes to the base of the instrument should occasionally be inspected and cleaned. Methylated spirit may be used if necessary.

If, at any time, the instrument appears to be badly out of adjustment the procedures listed below for the appropriate fault should be carried out:

(a) *Incorrect siphoning.* With the float chamber resting correctly on its knife-edge, adjust the back stop so that there is only a little play (about 1 mm) between the trigger and the trigger catch. Set the counterweight as far from the float chamber as possible and adjust the pen to read zero on the chart after siphoning, having made sure that the gate bearings of the pen arm are neither stiff nor unduly loose.

Set the front stop as high as possible and then pour water into the float chamber until the pen rises a little above the 4 mm line on the chart (Figure 8). Release the trigger and tilt the float chamber by hand on to the front stop. Lower the front stop while holding the float chamber on it until siphoning begins and then lock the front stop in that position.

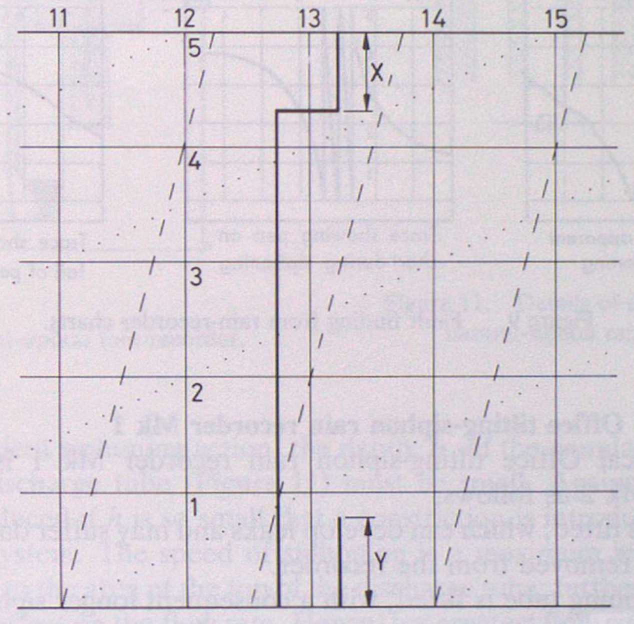


Figure 8. Pen trace used for balancing chamber.

Pour water into the float chamber again to a little over 4 mm and move the counterweight nearer to the float chamber until the chamber would tilt if the trigger were released. Mark the chart by turning the drum at this point. Pour more water into the float chamber until the chamber automatically tilts and siphons and note the point at which the pen returns to the chart after the float chamber has returned to the vertical. The best position for the counterweight is such that the pen returns to the chart at a distance above the zero line equal to the distance below the 5 mm line at which the float chamber will tilt when the trigger is released by hand, i.e. in Figure 8, X = Y. For example, if the float chamber will tilt when the pen rises to 4 mm and the pen returns to the chart at 1 mm after siphoning has taken place, the adjustment is satisfactory. The counterweight should then be locked in position.

The adjusting screw for the trigger should be set so that the trigger releases the float chamber when the pen indicates exactly 5 mm on the chart.

Finally, the pen lifter should be tested by pouring water into the float chamber until the pen indicates 2 mm on the chart and releasing the trigger and tilting the float chamber by hand; the pen should lift automatically from the chart. If this does not happen, the pen arm or pen-lifter rod has become bent. When the float chamber is vertical the pen arm should be close to, but not touching the pen-lifter rod.

(b) *Unstable zero.* If during a period when it is known that no rain has fallen, the trace on the chart is not parallel to the chart rulings, either the chart has not been set on the drum correctly or there is a fault in the drum or clock spindle. If the fault appears to be in the drum or clock it should be replaced.

(c) *Trace showing apparent prolonged siphoning* (Figure 9). Examine the instrument to see if (1) the siphon tubes are blocked or bent, (2) the knife-edges of the float chamber are not in the grooves or (3) the float is rotating. If the siphon tubes are damaged the float chamber should be replaced.

(d) *Trace showing the pen on the chart during siphoning* (Figure 9). Check that the pen-lifter is set correctly as described in (a) above. Check that the counterweight is set correctly and that nothing is preventing the float chamber from tilting.

(e) *Trace showing gradual fall of pen* (Figure 9). Examine the instrument to see if (1) the float is rotating, (2) there is a leak in the float chamber or (3) the pen arm is loose on the float rod.

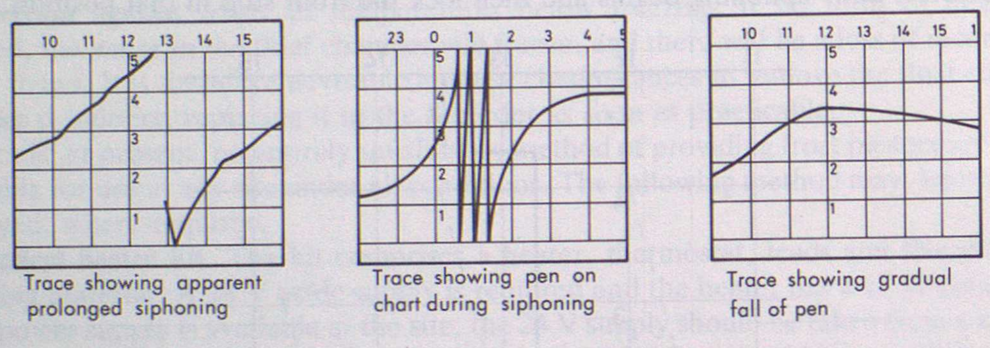


Figure 9. Fault finding from rain-recorder charts.

3.2 Meteorological Office tilting-siphon rain recorder Mk 1

The Meteorological Office tilting-siphon rain recorder Mk 1 is an earlier model, differing from the Mk 2 as follows:

(a) A metal float is fitted, which can develop leaks and may suffer damage during periods of frost unless removed from the recorder.

(b) Only one siphoning tube is fitted, with a consequent longer siphoning time of about 15 seconds.

(c) No rain-trap is fitted.

The absence of a rain-trap and the longer siphoning time create a small, though not necessarily negligible, error in recorded rainfall especially during periods of heavy rain.

A Mk 1 recorder can be converted to a Mk 2 model by replacement of its complete float chamber assembly with a Mk 2 assembly, though approximately 20 mm must be sawn off the funnel pipe to accommodate the rain-trap.

The general instructions regarding installation, method of use and maintenance of the Mk 1 recorder are similar to those for the Mk 2, where applicable.

3.3 Natural-siphon rain recorder

The method of operation of the natural-siphon rain recorder differs from the Meteorological Office tilting-siphon rain recorders in the manner in which the water is siphoned out of the float chamber when it has become full (Figure 10). The discharge tube, A, of the siphon is inside the coaxial with the tube connecting with the float chamber. The top of this outer tube is a polished glass cap, B, and the discharge tube comes up to within a very short distance of it. When the water in the outer tube rises to the top and flows over the bend, capillary action causes all the air to be pushed out and down the delivery tube so that a full flow is started at once. Similarly at the end of the siphoning, once air gets to the top of the tube the siphoning action is stopped immediately.

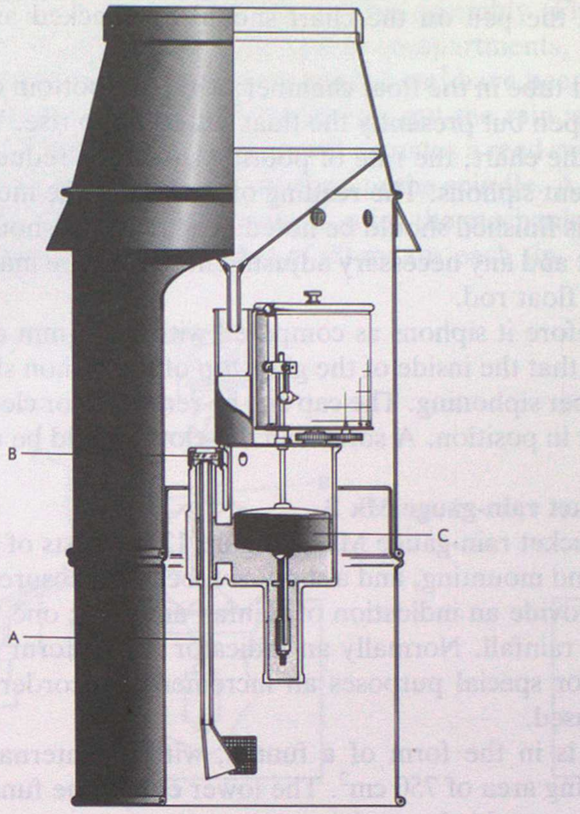


Figure 10. Natural-siphon rain recorder.

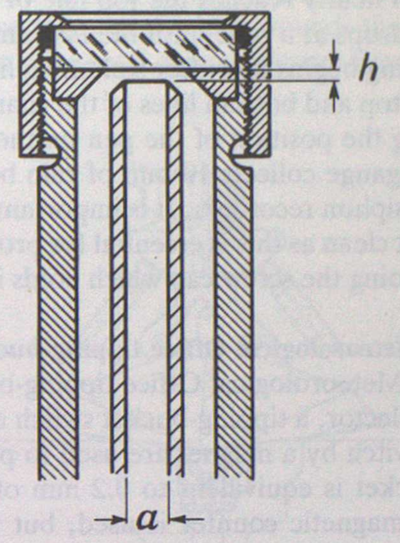


Figure 11. Details of siphoning tube of natural-siphon rain recorder.

To ensure an efficient siphoning action, the depth, h, of the annular space between the glass cap and the discharge tube (Figure 11) must be small. Against this, the speed of siphoning will be reduced if h is so small that a constriction is introduced into the flow of water through the system. The speed of siphoning is a maximum when the area of the annular ring is equal to the area of the top of the discharge tube; further increase of the ring area has little or no effect on the flow rate. Hence, for greatest flow conditions, the area of the ring need be no greater than the area of the tube. If a is the diameter of the discharge tube, this condition gives

$$\pi a\, h \text{ need be no greater than } \frac{\pi a^2}{4}$$

$$\text{or, } h \text{ need be no greater than } \frac{a}{4}$$

Thus if a is 10 mm, h need not be greater than 2.5 mm.

The brass rim at the top of the cover and funnel is 8 inches in diameter, and the rain is led from there via the funnel to a float chamber containing a light float C. The float has a float rod which runs in guides in the top and bottom of the float chamber and, protruding through the top of the float chamber, carries the pen which records on a chart fixed on a revolving drum. When siphoning occurs the pen falls vertically to the zero without coming off the chart.

The upper section of the recorder, comprising the funnel and cover, lifts off the base, and the instrument is usually installed so that the base of the upper section when in position is level with the surrounding ground. The rim is then 420 mm above ground level.

The routine care of the pens, chart changing and time marking, etc., are similar to those for the Meteorological Office instruments, and similar precautions should be taken in cold weather.

When first installed the position of the pen on the chart should be checked and, if necessary, adjusted as follows:

Water should be poured into the inlet tube in the float chamber; while the bottom of the float chamber is filling nothing will happen but presently the float will begin to rise. When the pen nearly reaches the top line of the chart, the rate of pouring should be reduced to single drops at a time until the instrument siphons. The reading of the pen at the moment siphoning begins and after siphoning has finished should be noted. The readings should be on the top and bottom lines of the chart and any necessary adjustments should be made by altering the position of the pen on the float rod.

The gauge collects 10 mm of rain before it siphons as compared with the 5 mm of the tilting-siphon recorders. It is important that the inside of the glass top of the siphon should be kept clean as this is essential for proper siphoning. The cap can be removed for cleaning by undoing the screw cap which holds it in position. A soft clean dry cloth should be used.

3.4 Meteorological Office tipping-bucket rain-gauge Mk 3

The Meteorological Office tipping-bucket rain-gauge Mk 3 (Figure 12) consists of a 750 cm^2 collector, a tipping-bucket switch and mounting, and a support tube. The closures of a reed-switch by a magnet are used to provide an indication of rainfall amounts; one tip of the bucket is equivalent to 0.2 mm of rainfall. Normally an indicator in the form of an electromagnetic counter is used, but for special purposes an incremental recorder or a magnetic-tape event recorder may be used.

750 cm^2 collector. This collector A is in the form of a funnel, with an internal rim diameter of 309 mm providing a collecting area of 750 cm^2. The lower end of the funnel is fitted with a skirt which has locking lugs moulded onto it.

Tipping-bucket switch mounting. This is a small funnel and tube B with a spoiler fitted inside the tubing to prevent swirling of the rain inside the tube.

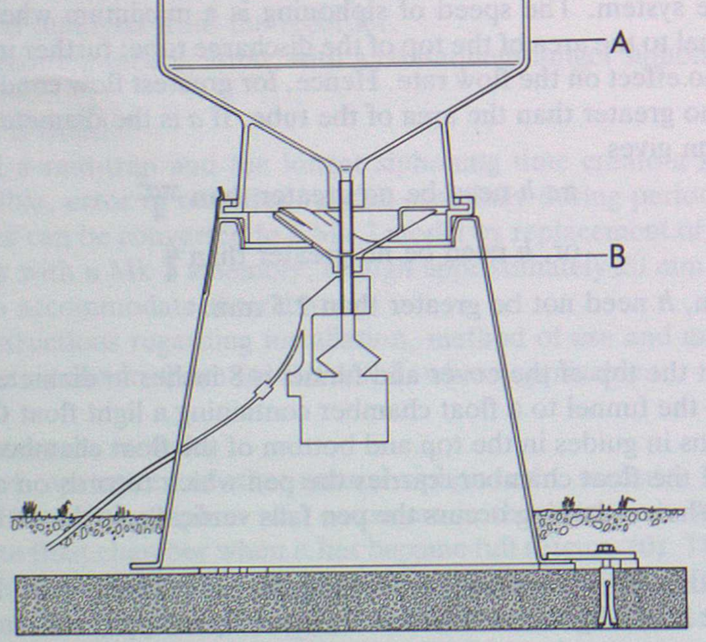


Figure 12. Meteorological Office tipping-bucket rain-gauge Mk 3.

Tipping-bucket switch Mk 3. This assembly (Figure 13(a)) consists of a stainless steel bucket A, divided into two equal compartments, mounted on a spindle. Rain is led into one compartment and when 15±0.2 cm^3 have been received, the bucket overbalances and tips. As this measured quantity tips out the rain is led into the other compartment. Each time the bucket tips, a magnet B actuates a reed switch C fitted on the casting. The magnet is fixed to a vertical rod attached to the spindle. A rectangualr shield surrounds the switch assembly and provides protection for the mechanism. The total contact closure time of the reed switch is of the order of 80 ms for each tip.

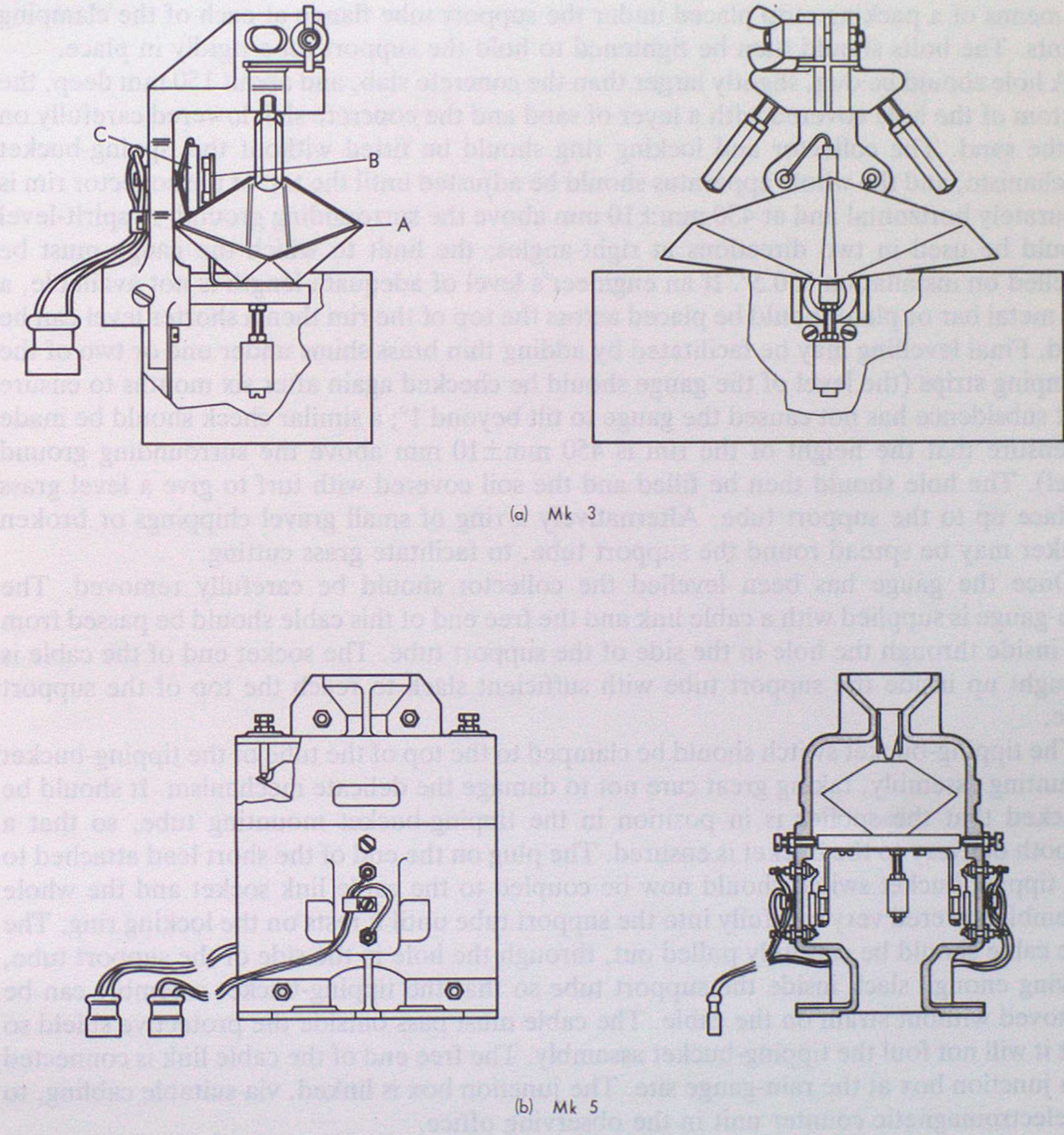


Figure 13. Meteorological Office tipping-bucket switches Mk 3 and Mk 5.

Installation. In addition to the items already mentioned above, the following materials are required for installation of the rain-gauge:

(a) A concrete slab with dimensions 600 mm × 600 mm × 50 mm.
(b) Three M6 × 76 mm Rawlbolts.
(c) Three 76 mm × 50 mm × 5 mm mild steel strips, each with a 7 mm diameter hole 25 mm from one end, to act as clamping strips.
(d) Three small brass or galvanised steel packing strips approximately 2 mm thick.

A hole, 10 mm in diameter, should be drilled in the support tube about 150 mm from the top (unless the support tube already has a hole in it when issued), to allow for the exit of the cable from the tipping-bucket switch. A rubber or neoprene grommet should be fitted in the hole.

The support tube should be placed on the concrete slab and three points marked symmetrically on the slab, each point about 30 mm out from the edge of the flange. Each point should then be drilled to accommodate a Rawlbolt. A clamping strip should be fitted on each Rawlbolt with the longer part of the strip overlapping the flange of the support tube. The support tube should be raised approximately 2 mm above the surface of the slab by means of a packing strip placed under the support tube flange at each of the clamping points. The bolts should then be tightened to hold the support tube rigidly in place.

A hole should be dug, slightly larger than the concrete slab, and about 150 mm deep, the bottom of the hole covered with a layer of sand and the concrete slab lowered carefully on to the sand. The collector and locking ring should be fitted without the tipping-bucket mechanism, and the whole apparatus should be adjusted until the top of the collector rim is accurately horizontal and at 450 mm±10 mm above the surrounding ground. A spirit-level should be used in two directions at right-angles; the limit to which the gauge must be levelled on installation is 0.5°. If an engineer's level of adequate length is not available, a flat metal bar or plate should be placed across the top of the rim then a shorter level can be used. Final levelling may be facilitated by adding thin brass shims under one or two of the clamping strips (the level of the gauge should be checked again after six months to ensure that subsidence has not caused the gauge to tilt beyond 1°; a similar check should be made to ensure that the height of the rim is 450 mm±10 mm above the surrounding ground level). The hole should then be filled and the soil covered with turf to give a level grass surface up to the support tube. Alternatively a ring of small gravel chippings or broken clinker may be spread round the support tube, to facilitate grass cutting.

Once the gauge has been levelled the collector should be carefully removed. The rain-gauge is supplied with a cable link and the free end of this cable should be passed from the inside through the hole in the side of the support tube. The socket end of the cable is brought up inside the support tube with sufficient slack to reach the top of the support tube.

The tipping-bucket switch should be clamped to the top of the tube of the tipping-bucket mounting assembly, taking great care not to damage the delicate mechanism. It should be checked that the spoiler is in position in the tipping-bucket mounting tube, so that a smooth delivery to the bucket is ensured. The plug on the end of the short lead attached to the tipping-bucket switch should now be coupled to the cable link socket and the whole assembly lowered very carefully into the support tube until it rests on the locking ring. The free cable should be carefully pulled out, through the hole in the side of the support tube, leaving enough slack inside the support tube so that the tipping-bucket assembly can be removed without strain on the cable. The cable must pass outside the protective shield so that it will not foul the tipping-bucket assembly. The free end of the cable link is connected to a junction box at the rain-gauge site. The junction box is linked, via suitable cabling, to an electromagnetic counter unit in the observing office.

Electromagnetic counter unit. The electromagnetic counter unit comprises a four or five digit counter mounted in a case complete with long-life leakproof batteries, and should be mounted indoors in a horizontal position. An external terminal block is provided for cable connection to the rain-gauge. Each tip of the bucket in the rain-gauge and consequent closure of the reed switch will cause the counter reading to advance one digit.

Plate I. Magnetic-tape event recorder

Magnetic-tape event recorder (MTER) Mk 2 and Mk 3. The MTER Mk 3, Plate I, is designed to record time and events on a four-track magnetic tape. The recording is made at a density of 200 bits per inch on a quarter-inch-wide magnetic tape, two tracks being used to record bucket events and the other two tracks to record time pulses at minute intervals from an electronic clock. Anti-coincidence circuits ensure that nominally coincident time and rainfall events are recorded sequentially. A special cassette holds 450 feet of tape, sufficient for a minimum capacity of over one million bits. The internal batteries provide enough power for approximately six months operation, depending on local conditions, e.g. temperature. An earlier, Mk 2, version of the MTER is discussed by Tonkinson (1975). The MTER Mk 2 differed from the MTER Mk 3 in having an electromagnetic clock, instead of the electronic type, and in incorporating two digital counters visible through windows in the case, to provide totals of bucket tips and elapsed time. These older Mk 2 MTERs have since been converted to Mk 3s.

At locations where hourly values of tipping bucket totals are required, this facility is provided by using the MTER with a counter interface. The counter interface consists of a small unit, powered by the MTER, which provides a duplicate contact closure to operate a remote electromagnetic counter.

For indoor installation the MTER should be placed, with its lid horizontal, on any flat surface within the observing office, care being taken to ensure that:

(a) Any shelf or desk on which the MTER is placed has a raised edge to stop the MTER from falling off owing to accident or misuse.

(b) The MTER is not located adjacent to central heating radiators, equipment likely to emit electrical disturbance or in any dirty or dusty environment.

(c) There is adequate space to permit the lid to be removed and the cassette changed, or alternatively to permit the MTER to be disconnected and removed elsewhere for cassette changing.

For outdoor installation the MTER should be placed on a 300 mm square paving slab located on the ground close to the rain-gauge. Care should be taken that the slab and MTER do not affect the rain-gauge exposure or, where installed in an instrument enclosure, the exposure of any other instruments in the vicinity.

Calibration. Once the rain-gauge is installed, the tipping-bucket assembly should be calibrated by measuring the volume of water required to cause one tip of the bucket. The first step is to 'wet' the surfaces of the bucket thoroughly. This is done by holding a 50 cm^3 burette, full of rain-water, vertically about 25 mm above the orifice of the funnel outlet and offset 25 mm, and allowing sufficient water to run out to produce 4 tips of the bucket. The water must be turned off as soon as the fourth tip occurs.

The burette is then refilled with rain-water and the burette reading adjusted until it reads zero. Water is run slowly from the burette into the collector to produce 3 tips of the bucket, the rate of flow being reduced to discrete drops before each tip; the burette reading should be noted after each tip. The process is repeated to give a total of 12 tips and the average volume per tip calculated. With a 750 cm^2 collector, each tip will be equivalent to $\frac{V}{75}$ mm of rainfall, where V is the average volume of water per tip. The calibration value of $\frac{V}{75}$ mm must lie within the range 0.196 to 0.204 mm per tip. The second burette reading from each series of 3 tips represents the total volume of both buckets and should not differ from 2 V by more than 0.3 cm^3. If isolated differences exceeding 0.5 cm^3 are obtained, repeat calibrations should be made. If there are two or more differences of 0.4 cm^3 or more then either the calibration method is at fault or there is excessive friction in the bucket bearings.

If the calibration values lie outside the range 0.196 to 0.204 mm then the bucket may require cleaning and, or, the bucket stops adjusting.

Maintenance and routine performance checks. At stations where a MTER is in use, the MTER input should be disconnected prior to any routine maintenance and performance checks. This helps to eliminate any spurious non-rainfall events on the tape. The MTER should be reconnected on completion of any check or maintenance.

Once the rain-gauge is installed and calibrated, care should be taken not to disturb the system; for instance movement may alter the calibration, or cause a nearly full bucket to tip. The collector should be kept clear of obstructions such as fallen leaves, etc., but this should be done gently, without disturbing the tipping-bucket switch. Should it be necessary to detach the collector, it should be eased free of the retaining lugs without shaking the support tube, and laid gently on its side, to avoid chipping the rim. The collector should be refitted to the support tube with equal care. The tipping-bucket unit within the support tube should not be touched.

At Meteorological Office sites three-monthly checks of the counter unit and six-monthly checks of the rain-gauge calibration are carried out and, if necessary, any sediment cleaned out of the bucket.

At about monthly intervals, selecting a period yielding a cumulative rainfall total exceeding 10 mm, the total rainfall measured using the standard rain-gauge, Mk 2 or Mk 3, should be compared with the product of the calibration and the number of tips obtained from the counter in the same period. Differences should not normally exceed 5 per cent of the standard rain-gauge value. A discrepancy greater than 10 per cent. indicates that the calibration has probably changed.

Should no counts be indicated during a period when appreciably more than 0.2 mm of rain has fallen and the air temperature has not immediately previously been well below 0 °C a check should be made by filling a 10 mm rain measure with water up to the 1.4 mm graduations, and then pouring this quantity of water (21 cm^3) into the collector whilst listening to hear whether during the pouring process the bucket tips. If the bucket does not tip it is probably sticking on its bearings. If the bucket does tip but the counter reading fails to advance the trouble may be due to a faulty counter or switch. If the bucket tips and the counter reading advances the bucket may be leaking. To check for leaks, the rain-gauge should be left for about six hours when there is no precipitation or dew, and then 0.6 mm (9 cm^3) of water from the rain measure poured in, left for a further hour or two, and then another 0.6 mm of water added. If the bucket does not tip during this further addition, then the bucket is leaking.

3.5 Meteorological Office tipping-bucket rain-gauge Mk 5

The Meteorological Office tipping-bucket rain-gauge Mk 5 is similar to the Mk 3 version in its principle of operation and differs mainly in constructional details.

The Mk 5 rain-gauge (Figure 14) consists of:

(a) A one-piece collector and support tube A manufactured from glass reinforced polyester resin. The collector has an aperture area of 750 cm^2, similar to the Mk 3 version.

(b) A cast-iron base B onto which the collector and tipping-bucket switch can be securely mounted.

(c) A Mk 5 tipping-bucket switch (Figure 13(b)). The Mk 5 switch differs from the Mk 3 version in the use of an aluminium alloy body casting to almost completely surround the bucket and switch mechanism, thus affording greater protection, and the incorporation of an additional magnet and reed switch. The extra switch permits the simultaneous operation of a MTER and an electromagnetic counter unit without the need for a separate interface. Also, should one or other of the switches develop a fault, the remaining switch can be used to provide continuity of rainfall record until such time as a complete replacement switch assembly can be fitted.

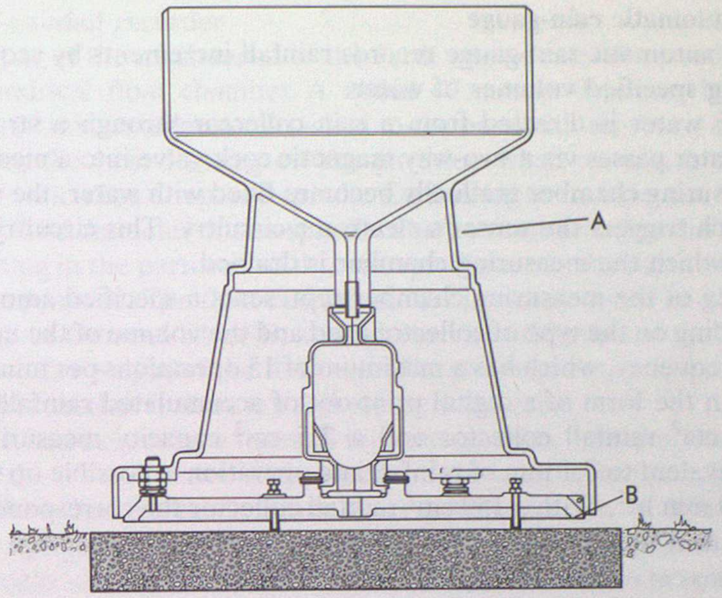


Figure 14. Meteorological Office tipping-bucket rain-gauge Mk 5.

Installation. A concrete slab, with dimensions 450 mm × 450 mm × 38 mm, should be positioned firmly in the ground with its upper face level and flush with the surrounding turf. The cast-iron base should be placed centrally on the slab and levelled, by adjusting the three levelling screws, until the bubble of the spirit-level fixed to the base is in a central position. The final levelling should, if possible, be made using an engineer's level so that the base is level to within 0.5° of the horizontal after which the locknuts on the levelling screws should be tightened and the level re-checked. If it is considered that there is any likelihood of the base being disturbed it may be bolted, through the central 12 mm diameter hole in the casting, to the concrete slab beneath it. It will be necessary to drill a hole in the slab and use a suitable means of attachment.

A thin film of silicone grease should be sprayed on all the machined surfaces of the base, and the tipping-bucket switch unit then placed on the support pads. The grommets supplied with the base should be pushed over the four positioning lugs to prevent excess movement of the assembly.

The leads from each of the reed switches end in a plug–socket assembly, a 5 m length of cable being sealed into the socket. One switch link is intended for operational use and the other as a spare, but each can be used for either purpose. The cable from each socket should be secured to the base, using cable ties, so that the plug and socket assembly is held within the diameter of the base without fouling the tipping-bucket assembly. The free end of one socket cable should be led outside the base.

The collector funnel should be placed on the base so that the locating lug in the base is lined up with the cut-out in the bottom of the collector. Levelling buttons fitted in holes in the collector bottom are pre-set and locked in position and should not be altered. Attached to the collector by short lengths of chain are three bolts. These bolts should be sprayed with silicone grease, passed through the holes in the bottom of the collector and the levelling buttons and screwed into the holes in the base until the levelling buttons touch the base.

Instructions for the maintenance and the routine performance checks of the Mk 5 tipping-bucket rain-gauge are broadly similar to those for the Mk 3 tipping-bucket rain-gauge.

3.6 Vaisala automatic rain-gauge

The Vaisala automatic rain-gauge records rainfall increments by sequentially collecting and discharging specified volumes of water.

In Figure 15 water is directed from a rain collector through a strainer A. From the strainer, the water passes via a two-way magnetic cock valve into a measuring chamber B. When the measuring chamber gradually becomes filled with water, the water level reaches a probe C which triggers the sensor's electronic circuitry. This circuitry controls the cock valve through which the measuring chamber is drained.

Each draining of the measuring chamber represents a specified amount of rainfall, the amount depending on the type of collector used and the volume of the measuring chamber. The draining frequency, which has a maximum of 15 operations per minute, is recorded on a display unit in the form of a digital print-out of accumulated rainfall amount.

With a 750 cm^2 rainfall collector and a 7.5 cm^3 capacity measuring chamber, each draining is equivalent to 0.1 mm of rainfall and operation is possible up to a maximum rate of rainfall of 90 mm h^{-1}. With a 150 cm^2 rainfall collector the corresponding figures are 0.5 mm and 450 mm h^{-1}.

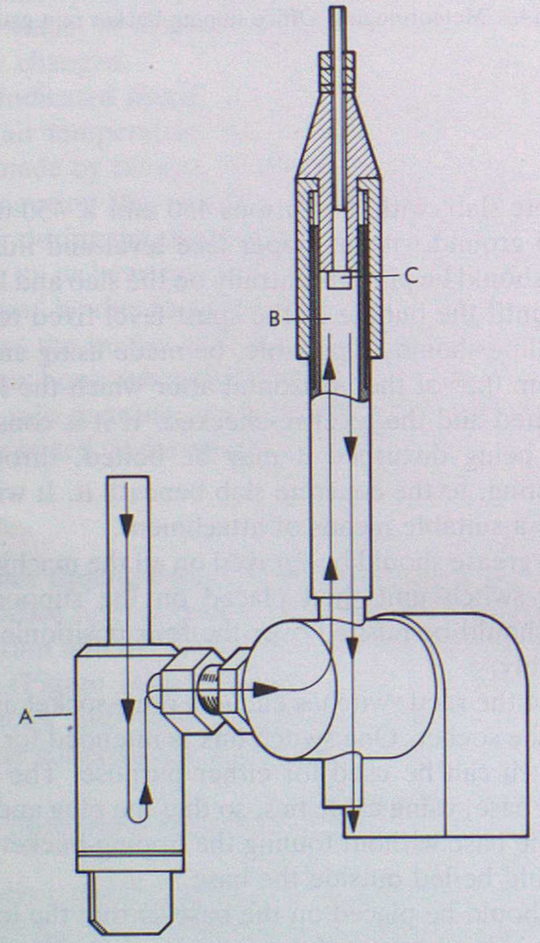


Figure 15. Principle of Vaisala automatic rain-gauge.

3.7 Jardi rate-of-rainfall recorder

The essential parts of the mechanism of the Jardi rate-of-rainfall recorder are shown in Figure 16. A cylindrical float chamber A about 40 mm in diameter has a bottomless extension B about 20 mm in diameter attached to the base with a circular opening C in the partition separating the two. Resting on the partition when no rain is falling is a light cylindrical float D which has a tapered spindle E attached to its base and extending down into the extension. The diameter of this spindle where it is attached to the float is the same as that of the opening in the partition so that the spindle closes the partition when the float rests on it but not otherwise. The float and spindle are attached to one end of a pivoted arm by means of a strip of German silver F; a weight on the other end of the arm is not quite sufficient to balance the weight of the float, spindle and strip. Any rain is led into one side of the float chamber so that it does not fall on the float itself.

When rain falls it can only escape through the annular space between the spindle and the opening C, hence the level of water in the float chamber, and consequently the float, rises until the rate of flow through this annular space equals the rate of inflow of the water, which in turn is proportional to the rate of rainfall. The angular motion of the pivoted arm from which the float is suspended, caused by the rising of the float, is magnified by a system of levers and transferred to a pen arm which causes a pen to record on a revolving drum. In order that F may be kept in the same vertical plane throughout, the end of the pivoted arm is in the form of an arc of a circle with the centre at the pivot.

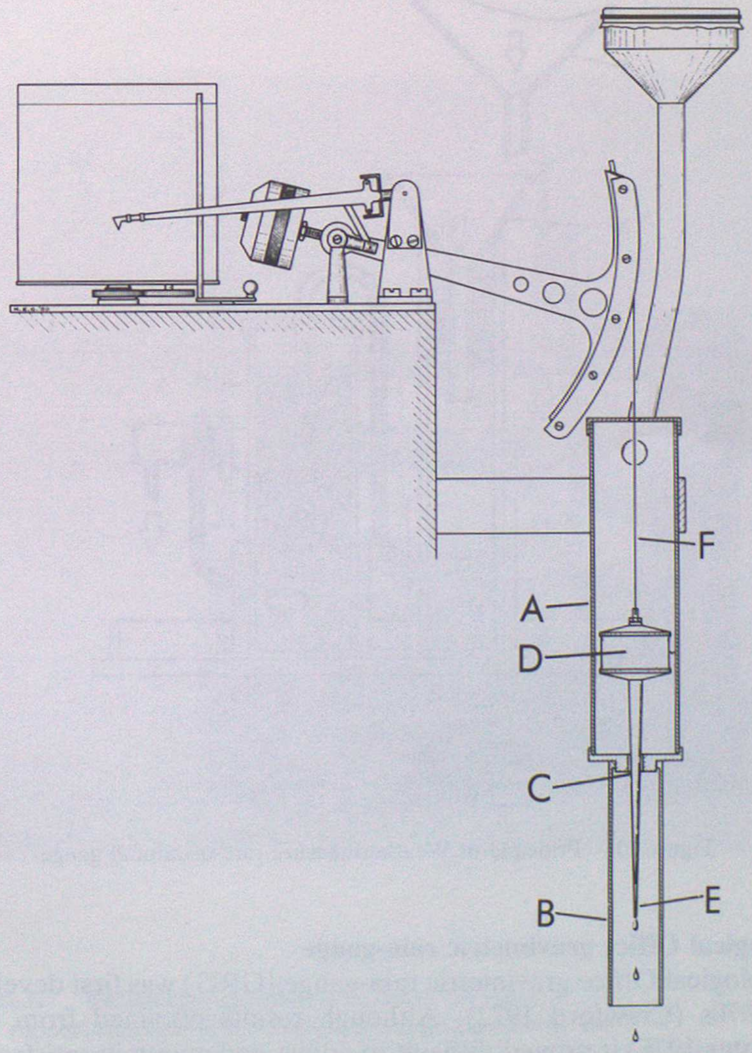


Figure 16. Jardi rate-of-rainfall recorder.

3.8 Weathermeasure rate-of-rainfall gauge

The Weathermeasure rate-of-rainfall gauge (Figure 17) is an electro-optical instrument which senses the passage of water droplets of uniform size through a kerosene bath. The number of droplets counted in a specified time is related to the rate of rainfall.

The gauge collector A, 200 mm in diameter, directs the collected rainfall to the bottom of a second funnel B mounted at the top of a small cylinder C which acts as a constant head reservoir. From an outlet near the bottom of the reservoir, a pipe rises vertically to near the top of the reservoir where it is formed into a 'U' bend. A small orifice in the top end of the pipe is positioned in the centre of an optical chamber D consisting of a clear glass cylinder filled with kerosene. If the reservoir and pipe are full of water, any additional water entering the reservoir will cause a flow of water from the orifice. Water leaving the orifice forms droplets of relatively uniform size which drop down through the kerosene to form a small pool of water at the bottom of the optical chamber. Excess water leaves the optical chamber through an overflow tube.

A light source, located at one side of the optical chamber, produces a narrow beam of light which is detected by a photocell, E, located diametrically opposite. Drops of water falling through the kerosene interrupt the light beam permitting individual drops to be counted when the photocell is connected to a suitable circuit. Each drop of water is equivalent to about 0.0083 mm of rainfall so that the rate of rainfall can be measured and recorded.

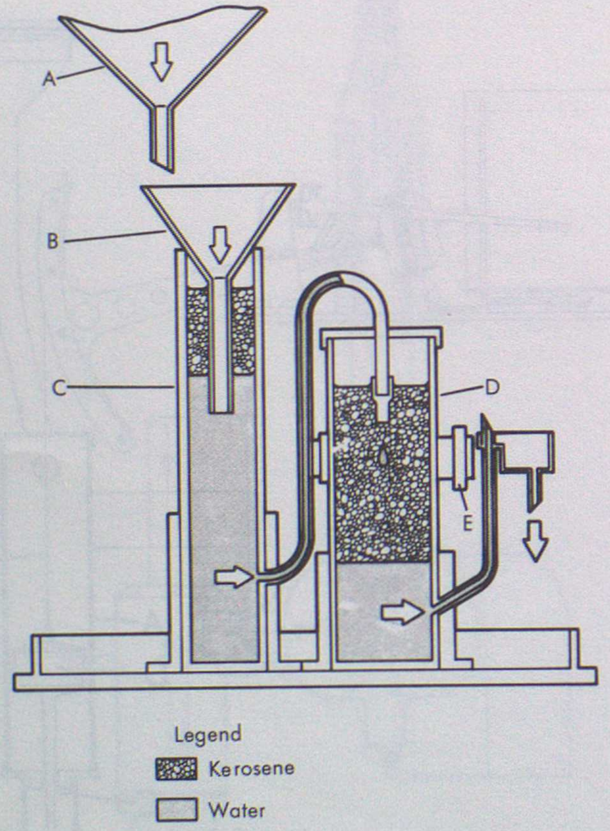
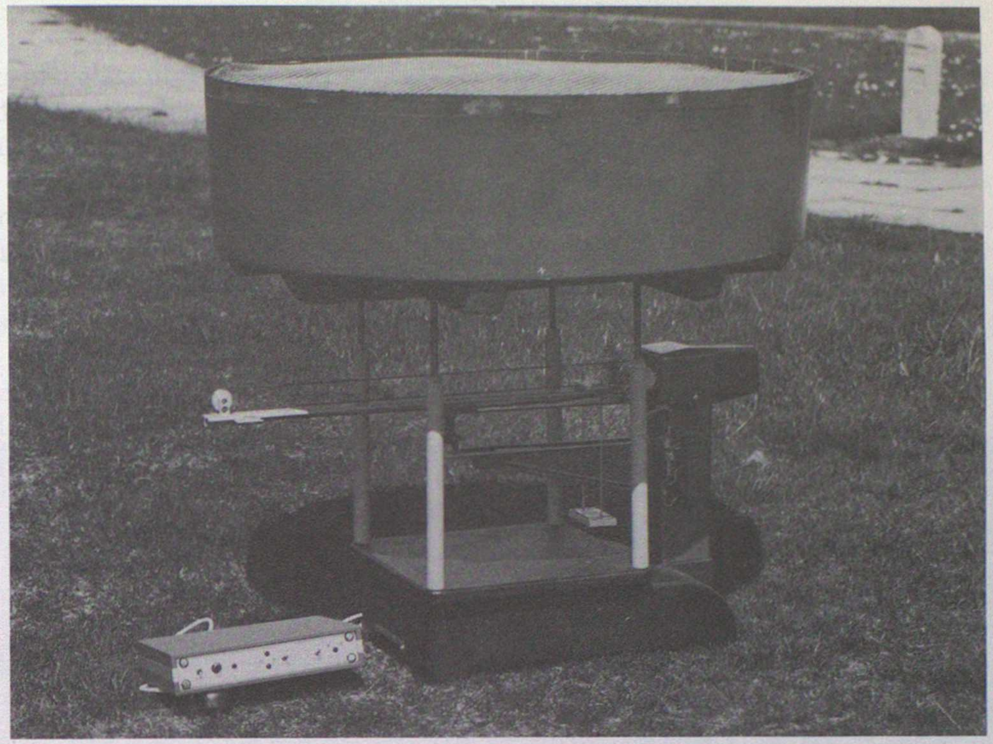


Figure 17. Principle of Weathermeasure rate-of-rainfall gauge.

3.9 Meteorological Office gravimetric rain-gauge

The Meteorological Office gravimetric rain-gauge (GRG) was first developed and tested in the early 1970s (Crawford 1972). Although results obtained from the GRG were promising (Painter 1975) it proved difficult to adjust and maintain satisfactorily and had a capacity of only 50 mm of rainfall. The most recent version of the GRG is discussed by Sherwood (1980) and is shown in Plates II(a) and (b). It is essentially a weight gauge and



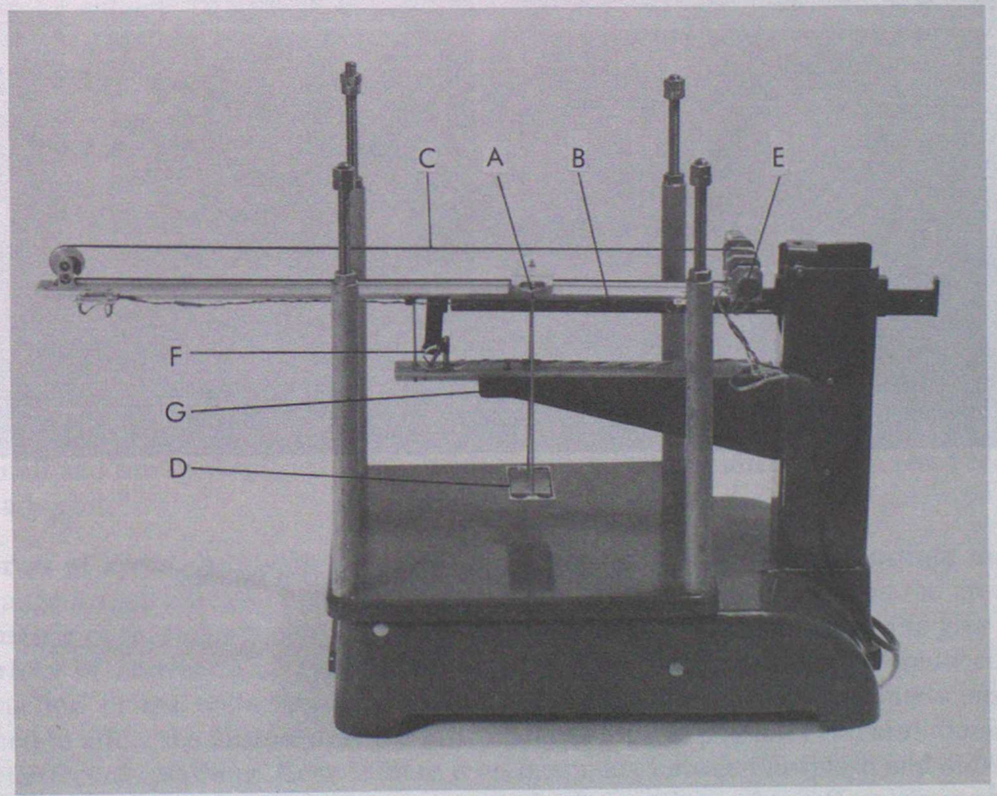


Plate II. Meteorological Office gravimetric rain-gauge
(a) (upper) complete with collecting pan and control box, and
(b) (lower) weighing-machine only; letters are explained in text on page 5–27.

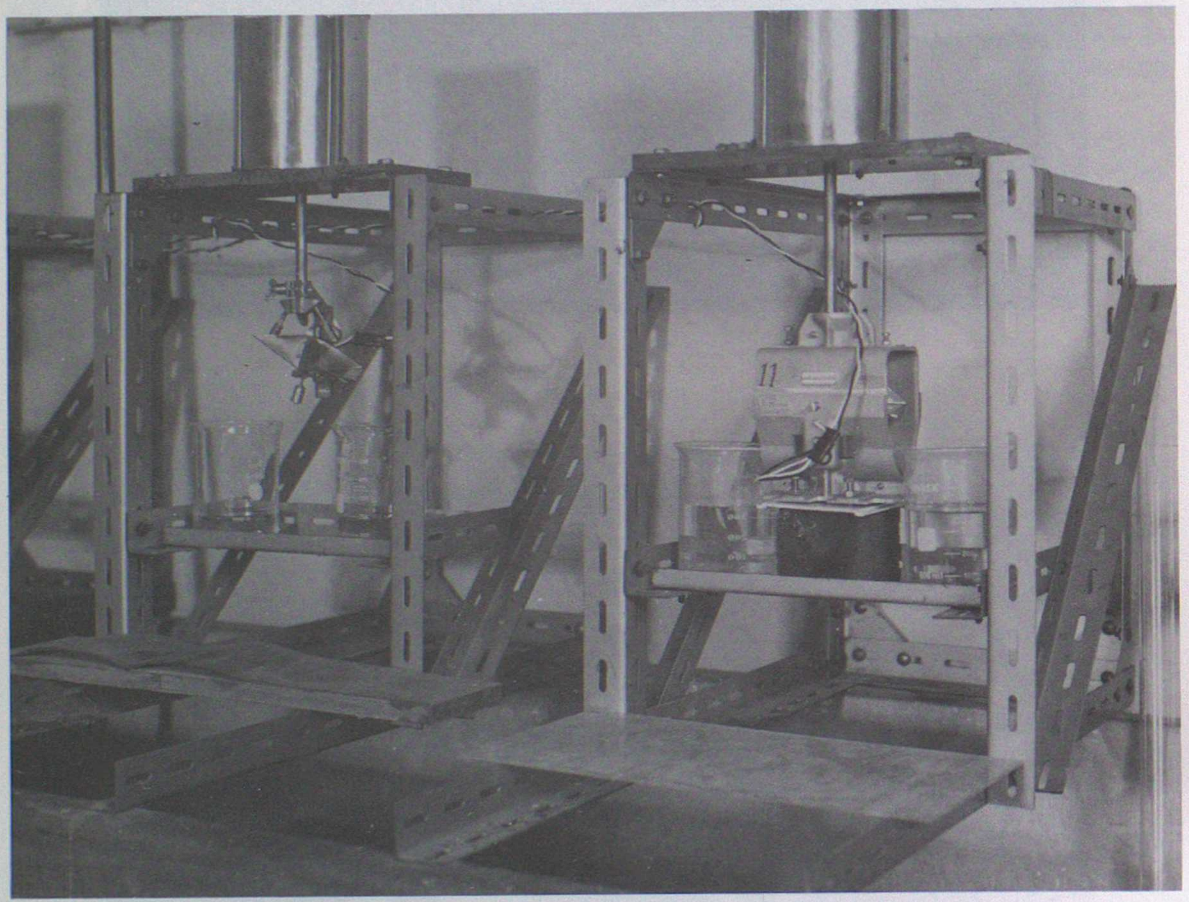


Plate III. Test rig for Mk 3 and Mk 5 tipping-bucket switches.

consists of a glass fibre collecting pan mounted on a weighing-machine placed in a pit in the ground. The weighing-machine automatically measures the weight of the pan and its contents; this weight is converted into a voltage analogue.

The diameter of the pan is 0.90 m and its depth 300 mm. About 25 mm below the top of the pan a strong stainless-steel wire mesh, covering the whole area of the pan, is supported on tightly stretched wires. The mesh wire is spaced at 8 mm intervals and provides support for a layer of granite chips. The pan is supported on an aluminium frame which is bolted to the platform of a bench-type weighing-machine with a nominal capacity of 100 kg. The whole assembly stands in a cylindrical concrete-lined pit, with the height of the frame adjusted so that the top of the pan is level with the surrounding ground. An annular area extending 2 m from the pan is also covered with granite chips so that this area and the pan form a homogeneous surface apart from a small gap between the pan and the concrete pit.

The weighing-machine is illustrated on Plate II (b). A jockey weight A slides along the upper flat surface of the aluminium balance arm B. A small disc of polytetrafluoroethylene fixed to the underside of the jockey ensures smooth motion without the need for additional lubrication. The lower part of the jockey is clamped to a driving belt C and suspended from the jockey is a weight box D. By the addition of weights to this box the overall weight of the jockey can be adjusted so that its maximum displacement along the balance arm corresponds to a convenient quantity of accumulated rainfall.

The endless non-slip driving belt to which the jockey is clamped passes over toothed pulley-wheels at each end of the balance arm. The pulley-wheel E at the inner end of the balance arm is driven by a small d.c. motor working through a reduction gearbox; this wheel is attached to the shaft of a precision potentiometer which provides an electrical output proportional to the displacement of the jockey. The polarity of the current to the motor is determined by two relays, actuated by an optical switch F attached to the end of the beam G, so as always to be in a direction which causes the jockey to be driven towards the equilibrium position. The optical arrangement is such that the cut-off is very sharp and the 'dead-space', when neither relay is energized, is minimal.

A magnetically activated reed relay is positioned at each end of the balance arm so that if the jockey reaches an extreme position the relay produces a signal which inhibits further movement of the jockey away from the centre of the arm.

Switches providing the choice of manual or automatic drive to the motor are mounted on the front panel of a control box (Plate II(a)) together with three light-emitting diodes which show whether the jockey is moving 'in' or 'out', or if it has reached one or other of the reed relay stops. The 0–100 mV output from the control box is equivalent to 0–100 mm of rainfall and can be displayed or recorded on any suitable millivoltmeter, chart recorder or data logger.

Sources of error. Although it is difficult, if not impossible, to demonstrate that any rain-gauge actually measures the amount of rain that would have fallen on the ground in the absence of that rain-gauge, for the GRG those factors which are known to give rise to the errors of conventional types of rain-gauge have been considerably reduced. The construction of the collecting area of the GRG together with its surrounds has been designed to affect the airflow over the instrument as little as possible, and also to minimize the net effect of splashing. Even if there is an inequality between in-splash and out-splash, the relatively large size of the pan will further reduce this effect upon rainfall measurements.

With regard to other sources of error, adhesion of water to the granite chips means that some water does not reach the pan, but obviously has no effect on the weight recorded by the GRG. Evaporation from the pan has often been recorded but this again can be isolated for periods when it is not raining, since the measurement of rain consists of the summation of the record when the weight is increasing. During periods favourable for the deposition of dew, the deposit may be abundant on grass while meagre or even absent on bare soil, concrete etc. The GRG has clearly indicated the weight of such deposits on a number of occasions. When, however, a period of rainfall is followed by a period of condensation, it is not always possible to distinguish between the two. The pressure differential between the free atmosphere and the pit under the collector pan in which the GRG is located needs to be only 3μbar to produce an apparent weight change equivalent to 20 g (0.03 mm of rainfall), the discrimination of the GRG. Hence, even in light winds the GRG may be pushed off balance by gusts though so far errors from this source have not exceeded the equivalent of ±0.05 mm of rainfall.

Performance of the GRG. Painter compared measurements made with the original GRG with measurements made with a series of standard total rain-gauges Mk 2. Sherwood made a comparison between the improved GRG and a single standard rain-gauge. The results of the two comparisons are expressed in the equations

$$R = 1.042\,R_s + 0.220 \quad \text{(Painter)}$$
$$R = 1.06124\,R_s + 0.0664 \quad \text{(Sherwood)}$$

where R is the rainfall equivalent as measured with the GRG and R_s the rainfall measured with the standard rain-gauge. The systematic error of about 0.07 mm to 0.2 mm between the GRG and the standard rain-gauge can be attributed to the water which remains in the bottle of the standard rain-gauge when it is read and which subsequently either evaporates or is recorded as a 'trace.' The general difference of +4 to +6 per cent in catch between the GRG and the standard rain-gauge is consistent with previous evidence (Robinson 1969) that a ground level rain-gauge will catch about 5 per cent more rain than a well-exposed standard rain-gauge.

4 TESTING AND CALIBRATION OF RAIN-GAUGES

4.1 Testing of total rain-gauges

The funnel and inner and outer cans of the Meteorological Office rain-gauge Mk 2 are tested for leaks by immersing, inverted, in water. The dimensions of the various components are measured and checked for compliance with the appropriate tolerance. In particular, the brass rim of the collector must be within ±0.2 inch of the nominal diameter for any single internal diameter and within ±0.1 inch for the mean of any four internal diameters.

The 150 cm^2 collector of the Mk 3 rain-gauge is checked for cylindricality and correct dimensions.

4.2 Testing and calibration of recording rain-gauges

The Mk 2 tilting-siphon rain recorder and the Mk 3 and Mk 5 tipping-bucket rain-gauges are subjected to leak and dimensional checks in a similar manner to total rain-gauges. In addition, the adjustment (page 5-13) and calibration (page 5-21) procedures are also carried out prior to issue. Plate III shows the test rig for tipping-bucket switches.

5 EVAPORATION

5.1 General

Measurement of evaporation from free water surfaces and the soil, and transpiration from vegetation are of great importance in agricultural and hydro-meteorological studies and in the design and operation of reservoirs and irrigation and field-drainage systems.

The measurement of evaporation is much more difficult than the measurement of precipitation, and reliable absolute values of the loss of water by evaporation from the surface of the earth over areas of any appreciable size have not yet been obtained. The following factors affect the rate of evaporation, sometimes indirectly, from any body or surface:

(a) Total radiation, solar and terrestrial.
(b) Temperature, both of the air and the evaporating surface.
(c) Wind speed at the surface.
(d) Humidity at the surface.
(e) Amount of moisture in the surface available for evaporation.
(f) Nature of the surface (e.g. roughness).

In addition to the surface values of wind speed, humidity and temperature, their variation with height in the lowest layers of the atmosphere also affects the rate of evaporation, which therefore varies greatly over comparatively small distances. Conditions also arise in which there is a net condensation of water vapour onto the surface, i.e. dew or hoar frost is deposited.

5.2 Units of measurement

The rate of evaporation from a surface can be expressed as the volume of liquid water evaporated per unit area in unit time. This is equivalent to a depth of liquid water lost per unit time from the whole area and evaporation is usually expressed in this way. The unit of time is usually either an hour or a day and the depth may be expressed in millimetres or centimetres.

5.3 General principles of evaporation gauges

Evaporation from any natural solid surface can be considered as taking place in two separate stages, (a) the diffusion of water, either as liquid or vapour, through the solid to the surface, and (b) removal of the water from the surface. The first stage depends on the factors (e) and (f) above, which are complicated functions of the type and condition of the vegetation (e.g. the species, maturity and extent), the type of soil, the condition of the soil and the subsoil and whether the surface is wet. The second stage depends on the wind speed near the surface, its variation with height, and the vertical distribution of the specific humidity. Only the second stage occurs with water surfaces such as lakes or reservoirs.

The term 'evaporimeter' or 'atmometer' is applied to a number of devices by which the water loss from a saturated surface is measured. They do not measure directly either evaporation from natural water surfaces, actual evapotranspiration (the total water loss due to soil evaporation and plant transpiration) or potential evapotranspiration (that which would occur were there is an ample supply of water), and the values obtained cannot therefore be used without adjustment to arrive at reliable estimates of lake evaporation and actual and potential evapotranspiration from natural surfaces.

5.4 Exposure and siting of evaporation pans and tanks

Evaporation is measured by observing the change of level of the free water surface in a pan or a tank. These, the most widely used types of evaporation gauges, form the basis of several techniques for estimating both lake evaporation and evapotranspiration.

Three main types of exposure are used for evaporation pans and tanks:

(a) Sunken, where the main body of the pan (or tank) is below ground level, the evaporating surface being at or near the level of the undisturbed ground surface.
(b) Above ground, where the whole of the pan and the evaporation surface are at some small height above the ground.
(c) Floating, where the pans are mounted on anchored floating platforms on lakes or water bodies.

Pans installed above the ground are inexpensive and easy to install and maintain. They stay cleaner than sunken tanks as dirt does not splash or blow into the water from the surroundings to any large extent. Any leaks that develop after installation are relatively easy to detect and rectify. However, the amount of water evaporated is greater than from sunken pans of comparible size because of the additional radiant energy intercepted by the pan sides. Adverse side-wall effects can be largely eliminated by using an insulated pan but this adds materially to the cost.

Sinking the pan into the ground tends to eliminate unacceptable boundary effects, such as radiation on the side-walls and heat exchange between the atmosphere and the pan proper. The disadvantages are that more debris is collected, the pan is difficult to clean, leaks cannot be easily detected and rectified, and the height of adjacent vegetation can be critical. Moreover, appreciable heat exchange takes place between the pan and the soil, and this depends on many factors such as soil type, moisture content and vegetation cover.

Evaporation from a pan floating in a lake more nearly approximates to evaporation from the lake than from an onshore pan exposed either above or below ground although its heat storage properties are different from those of the lake. A floating pan is, however, influenced by the particular lake in which it floats. Operational difficulties are the main disadvantages of floating pans and splashing can render the data unreliable. They are also costly to install and repair.

In siting the pan four factors have to be taken into account:

(a) Out-splashing of water from the pan in high winds.
(b) In-splashing of rain from the surrounding ground.
(c) The necessity of ensuring similar exposures of the rain-gauge and evaporation pan, so that the amount of precipitation caught by the pan may be accurately represented by the amount caught by the rain-gauge.
(d) The amount of exposure necessary to make the reading representative of the surroundings. If the exposure is too sheltered the instrument will not record the variations in evaporation which take place in more exposed areas due to variations in wind strength.

Items (a), (c) and (d) have to be balanced against one another and a satisfactory compromise made. A fairly sheltered position has to be chosen as the rain-gauge must be sited in accordance with the principles laid down on page 5-2, and must also be close to the tank itself. A distance of 1 m to 3 m away from the tank is desirable. Item (b) is kept to a minimum by growing grass on the tank surrounds.

The site should be fairly level and free from obstructions. Obstructions such as trees, buildings, or nearby shrubs should not be closer than four times the height of the object above the pan. Where necessary the plot should be fenced to protect the instruments and to prevent animals drinking the water; the fence should not affect the wind structure over the pan. Grass, weeds, etc. must be cut sufficiently frequently to keep them below the level of the pan rim. Under no circumstances should the pan be placed on a concrete slab or over asphalt etc.

5.5 The Meteorological Office standard evaporation tank

The Meteorological Office standard evaporation tank, Figure 18, is square with sides 1.83 m long and 610 mm deep, and is constructed of wrought-steel plates, overlapped and riveted together. Around the outside, 76 mm from the top, is riveted a horizontal flange 25 mm wide, and the tank is sunk into the soil up to the level of the flange; the top of the tank is thus 76 mm above the surrounding ground. The inside surface of the tank is painted matt black and the external surface is painted with a black bitumen paint.

To avoid trouble due to ripples on the surface of the water, the measurement of the depth of water is made inside a stilling well. This is box-shaped without a top and made of galvanized iron. It measures 100 mm square by 305 mm deep, with a round hole in the centre of the base. It is suspended in the tank at the centre of one of the tank sides, by two flat metal hooks attached to one of its sides so that, when in position, its top is level with the top of the tank.

The depth of water is measured with a hook gauge, Figure 19. This consists of a graduated brass rule with a channel in its face in which a slide A, which has a vernier engraved on it, can be moved by a rack and pinion movement controlled by the knob B. The hook is a piece of brass attached to the slide with a straight horizontal indicating edge on the same horizontal level as the lowest vernier graduation. The front edge of the slide is kept flush with the graduated face of the channel by means of a spring whose tension can be adjusted by means of a small screw C. A moveable clamp D provides support by which the

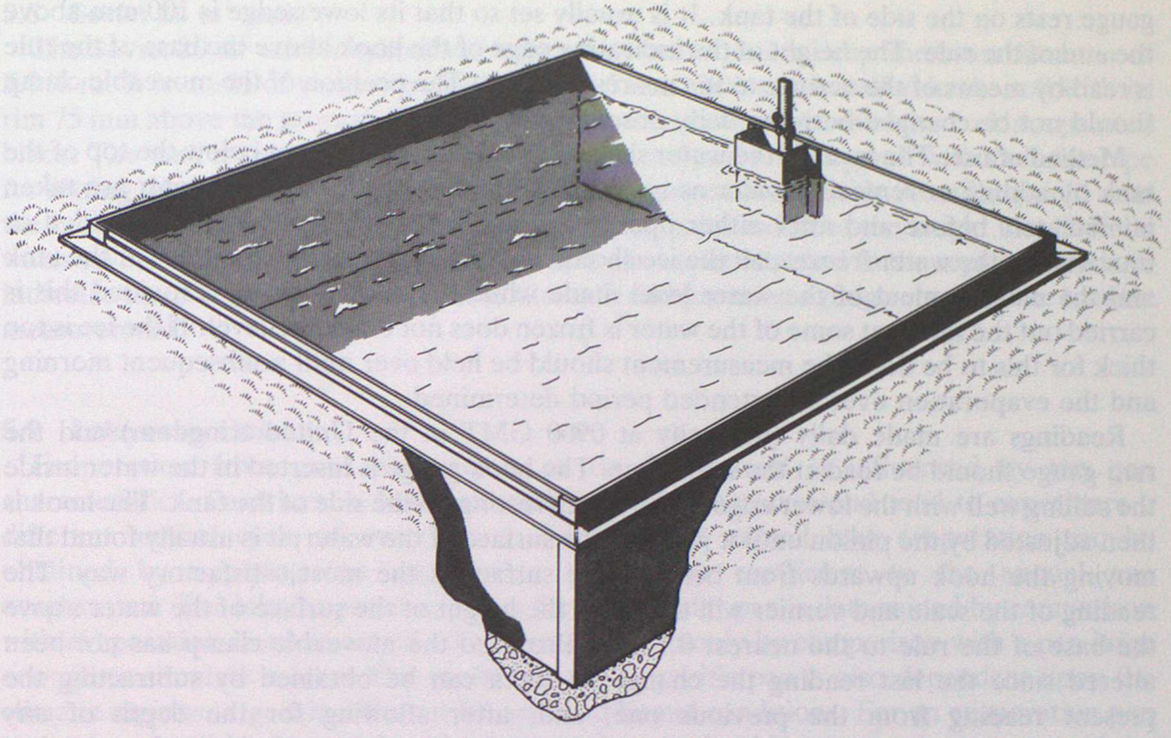


Figure 18. Meteorological Office standard evaporation tank.

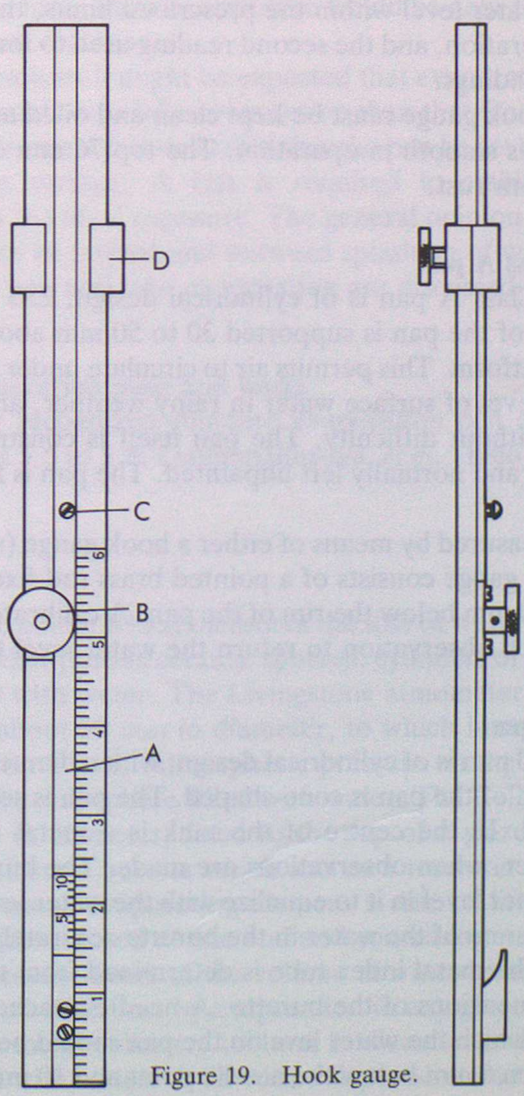


Figure 19. Hook gauge.

gauge rests on the side of the tank. It is usually set so that its lower edge is 100 mm above the end of the rule. The height of the indicating edge of the hook above the base of the rule is read by means of the vernier to the nearest 0.1 mm. The position of the moveable clamp should not be changed between daily observations.

Method of use. The level of the water should be kept at 50 to 75 mm below the top of the tank by adding or removing water as required. Readings of the depth of water are taken immediately before and after either operation to measure the depth of water added or removed. If the water freezes, all the ice should be broken away from the sides of the tank and the measurement of the water level made while the ice is floating. Provided this is carried out the fact that some of the water is frozen does not effect the level. If the ice is too thick for this to be done the measurement should be held over until a subsequent morning and the evaporation over an extended period determined.

Readings are made daily (normally at 0900 GMT in the United Kingdom) and the rain-gauge should be read at the same time. The hook gauge is inserted in the water inside the stilling well with the lower edge of the clamp resting on the side of the tank. The hook is then adjusted by the pinion until it just cuts the surface of the water; it is usually found that moving the hook upwards from beneath the surface is the most satisfactory way. The reading of the scale and vernier will then give the height of the surface of the water above the base of the rule to the nearest 0.1 mm. Provided the moveable clamp has not been altered since the last reading the change in depth can be obtained by subtracting the present reading from the previous one, and, after allowing for the depth of any precipitation, the evaporation or condensation can be found. If water has to be added or removed to keep the water level within the prescribed limits, the ordinary reading should be made before the operation, and the second reading used to form the basis of comparison with the subsequent readings.

Maintenance. The hook gauge must be kept clean and oiled at intervals so that the rack and pinion movement is smooth in operation. The top 76 mm of the tank and the flange should be kept free from rust.

5.6 United States Class A pan

The United States Class A pan is of cylindrical design, 250 mm deep and 1.207 m in diameter. The bottom of the pan is supported 30 to 50 mm above the ground level by an open frame wooden platform. This permits air to circulate under the pan, keeps the bottom of the pan above the level of surface water in rainy weather, and enables the base of the pan to be inspected without difficulty. The pan itself is constructed of galvanized iron, copper or monel metal and normally left unpainted. The pan is filled with water to 50 mm below the rim.

The water level is measured by means of either a hook gauge (see above) or a fixed-point gauge. The fixed-point gauge consists of a pointed brass rod fixed in a stilling well so that its tip is located 60 to 70 mm below the rim of the pan. A calibrated container is used to add or remove water at each observation to return the water level to the fixed point.

5.7 Soviet GGI-3000 pan

The Soviet GGI-3000 pan is of cylindrical design, with a diameter of 618 mm and a depth of 600 mm. The bottom of the pan is cone-shaped. The pan is set in the soil with its rim 75 mm above the ground. In the centre of the tank is a metal index tube upon which a volumetric burette is set, when observations are made. The burette has a valve, which is opened to allow the water level in it to equalize with the water level in the pan. The valve is then closed and the volume of the water in the burette accurately measured. The height of the water level above the metal index tube is determined from the volume of the water in the burette and the dimensions of the burette. A needle attached to the metal index tube indicates the height to which the water level in the pan should be adjusted. The water level is maintained at between 5 mm below the needle point and 10 mm above the needle point.

5.8 Soviet 20 m^2 tank

The Soviet 20 m^2 tank is cylindrical with a flat bottom, is 2 m deep and has a diameter of 5.046 m. It is made of welded iron sheets 4 to 5 mm thick and installed in the soil with its rim 75 mm above the ground. The inner and exposed outer surfaces of the tank are painted black. The tank is provided with a replenishing vessel and a stilling well with an index pipe for setting the volumetric burette when making measurements. Inside the stilling well, near the index pipe, a small rod terminating in a needle point indicates the height to which the water level is to be adjusted. A graduated side glass tube attached to the replenishing tank indicates the amount of water added to the tank and provides a rough check of the burette measurement.

5.9 Lake evaporation

Evaporation from pans exposed in or on the ground is influenced by the pan characteristics. Pans have a lower thermal capacity than lakes and tend to experience a different annual cycle of evaporation. Estimates of annual lake evaporation can be obtained by applying the appropriate lake-to-pan coefficient to the annual pan evaporation. The lake-to-pan coefficient for a particular pan is determined by comparison with evaporation from an actual lake, or more commonly by comparison with a pan large enough to simulate a lake. The coefficient for a specific pan is also dependent upon the climatic regions, e.g. it is different for arid and humid conditions. For an evaporation pan to serve as a valid index to lake evaporation, the pan should be exposed so as to avoid the environmental effect of the lake. Such an exposure would be near the lake, but on the side towards the prevailing wind direction.

From exposure considerations it might be expected that evaporation from a floating pan would be a better approximation to lake evaporation than that from a land based pan. To ensure greater representativeness it is desirable that the pan be set up with a minimum rim exposure above the lake surface. A raft is required to stabilize the pan and this immediately detracts from the ideal exposure. The general opinion on floating pans is that data are unreliable because of inward and outward splashing of water.

The factors influencing pan and lake evaporation are discussed by Hounam (1973).

5.10 Comparison of evaporation pans and tanks

There is no universally recognized standard evaporation pan or tank. In addition to those described in sections 5.5 to 5.8, Gangopadhyaya *et al.* (1966) describe and compare various other types.

5.11 Atmometers

An atmometer is an instrument which measures the loss of water from a wetted surface. The wetted surfaces are either porous ceramic spheres, cylinders or plates or exposed filter paper discs kept saturated with water. The Livingstone atmometer has as the evaporating element a hollow sphere about 50 mm in diameter, to which is attached a glass or metal tube dipping into a reservoir bottle. Atmospheric pressure on the surface of the water in the reservoir keeps the tube and sphere filled with water. The Bellani atmometer consists of a ceramic disc, 85 mm in diameter, fixed to the top of a glazed ceramic funnel, into which water is conducted from a burette which acts as a reservoir and measuring device. The Piche evaporimeter has as evaporating element a disc of filter-paper attached to a graduated measuring cylinder, closed at one end and containing water to keep the porous surface wet. Successive measurements of the volume of water remaining in the graduated tube will give the amount of water lost by evaporation in any given time. The Hirata-type evaporimeter consists of a metal cylinder, 100 mm in diameter and 50 mm deep, filled to about three-quarter depth with water. A lid with a depression and a hole in the middle is crimped to hold a filter paper of the same diameter as the cylinder. A piece of gauze, in contact with the filter paper and extending through the hole in the lid to the water, keeps the filter paper moist.

Although atmometers are frequently considered to give a relative measure of the evaporation from plant surfaces, their measurements do not, in fact, bear any close relation to evaporation from natural surfaces. While atmometers have the attraction of being inexpensive and simple to use there appears to be no really satisfactory method of exposing them and the influence of difference in exposure on the indicated evaporation is often large. Their readings are also seriously affected by the deposition of dust on the porous surfaces. The Piche evaporimeter is, in addition, very sensitive to wind speed and the shape and method of mounting the filter paper make it difficult to standardize the effectiveness of the evaporating surface. While it may be possible to relate the loss from atmometers to loss from a natural surface, a different relation may be expected for each type of surface and for different climates.

5.12 Evapotranspirometers

An evapotranspirometer is a container of soil and vegetation from which the water loss is measured by weighing or accounting for all incoming water at the surface and all outflow from the bottom of the container. To minimize the boundary effects, the evapotranspirometer must be quite large. The soil in it should be undisturbed in order to retain the natural soil profile and its water-holding characteristics. The surface should be covered with vegetation typical of the area in density, weight and species. Evapotranspirometers, the bottoms of which permit free downward flow of water, are called lysimeters. A suction force equivalent to that in the natural soil must be applied at the bottom of the lysimeter to avoid the collection of excess water in the air–soil–water interface.

If the vegetation and soil moisture in the evapotranspirometer can be maintained exactly the same as those in the surrounding soil, it is theoretically possible to measure actual evapotranspiration, but this is difficult to achieve in practice because of the artificial boundaries created by the container.

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APPENDIX 1

METEOROLOGICAL RECORDING INSTRUMENTS — GENERAL CONSIDERATIONS CONCERNING CONSTRUCTION, MAINTENANCE AND OPERATION

CONTENTS

LIST OF DIAGRAMS

LIST OF PLATES

APPENDIX 1

A.1 RECORDING METHODS

A.1.1 Introduction

The effect of friction on the accuracy of a recording instrument is generally larger and more serious than in a comparable indicating instrument, especially when a pen, writing continuously on paper, is used to record the results. The friction between the pen and the paper is usually much larger than the total amount of friction in the bearings of the instrument; the concept of adequate control thus arises.

The effect of friction is to impose a certain force on the indicating mechanism in the opposite direction to that in which the variable element is causing the mechanism to move. This force causes the reading of the instrument to be in error by a certain amount. The 'control' of the instrument may be defined as the force which must be applied to the indicating mechanism at the point where it is recording (e.g. at the pen) to keep the indication constant when the value of the element which is being recorded changes by one unit. This is equal to the force required to move the indicating mechanism over one unit of the scale provided the measured element remains constant. The greater the control the less will be the effect of friction and the more detailed will be the record. In any case the control should be such that the maximum effect of the friction on the reading should be less than the least change it is desired to record. If this is not so, the errors will be markedly different for rising and falling values of the element recorded and there will be 'lost motion' when the variable element reaches a maximum or minimum value.

A.1.2 Recording charts

There are several methods by which the indication of an instrument can be made to give a permanent record. In the majority of these the record is in the form of a line on a sheet of paper, and is measured by reference to the position of the line on the paper. The properties of the paper are thus of some importance.

Good chart paper is manufactured so that its fibres lie largely in one direction ('downboard'). These fibres are hygroscopic and swell slightly in a lateral direction when they absorb water. Thus it is found that an instrument chart changes its dimensions when it is soaked in water, or to a somewhat lesser extent when the humidity changes, and the magnitude of the change in any direction depends on the direction of the fibres. All Meteorological Office charts are cut with the time-scale 'downboard', and it is found that the change in length in this direction when the chart is immersed in water after being in a normal room atmosphere is about 0.2–0.3 per cent. On the other hand the change in length in a direction perpendicular to this is 2.5–3.0 per cent, i.e. 10 times as much. The chart will not of course become soaked in normal use, but experiments have shown that the changes in dimensions are very nearly as much when the charts are exposed in a humidity chamber and the relative humidity is altered from about 50 per cent to about 100 per cent. The change in length 'downboard' is 0.1–0.2 per cent, and the change in length in a perpendicular direction is 1.5–2 per cent.

In very accurate work it is thus necessary to have two datum lines drawn on the chart at fixed positions; these can be used as base lines to enable zero errors (due to chart slipping or being inserted wrongly) and changes in scale value (due to the chart altering in size before the record was made) to be measured and allowed for.

A.1.3 Pen recorders

In most meteorological instruments using pen recording the pen rests lightly on a chart wrapped around a vertical cylindrical drum. The drum is rotated at a constant speed, and as the element to be recorded varies the pen moves up and down the chart. To reduce friction, it is necessary to adjust the pressure of the pen on the chart to the minimum consistent with a clear record. This is achieved in many Meteorological Office instruments by means of the gate suspension (Figure A1). The pen arm is suspended in a small gate, A, so that it can rotate freely about the gate axis. The gate itself is fixed to a collar, B, and can be rotated about an axis parallel to the pen arm, i.e. its inclination to the vertical plane containing the pen arm can be varied. When the axis of the gate is in this vertical plane there is no tendency for the pen arm to move in one direction or the other, but when the gate is inclined to the vertical plane there is a component of the weight of the pen arm which exerts a moment about the gate axis and causes the pen either to press on the chart or to fall away from it. The pressure between the pen and the paper can thus be adjusted to a suitable value which remains practically independent of the position of the pen on the chart provided the pen arm is perpendicular to the pen-arm spindle. It is normally found that an inclination of the gate axis of about 10° to the vertical is quite sufficient.

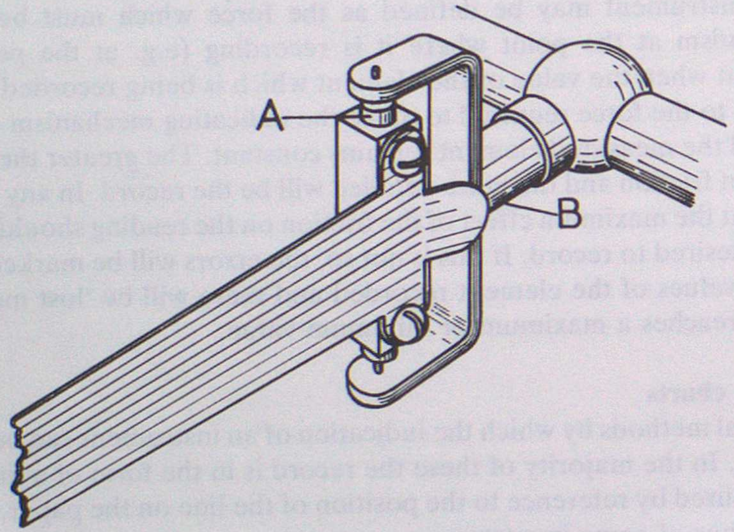

Figure A1. Gate suspension for pen arm.

There are two main ways in which the changes in the variable element being recorded are converted into changes of the position of the pen. In the first, the point of support of the pen arm is moved in a direction perpendicular to the time axis on the chart; the hour lines on the chart are straight lines and the length of the pen arm is immaterial. In the second, the changes in the variable element are converted into angular movements of a spindle on which the pen arm is mounted; the hour lines are approximately arcs of circles, with radii equal to the length of the pen arm (measured from the axis of the pen-arm spindle to the point of the pen) and with their centres on the plane through the pen-arm spindle parallel to the time axis. The true hour lines are not exactly arcs of circles because the pen writes on a cylinder and not on a plane surface.

It is necessary to ensure that the chart is printed for the correct pen-arm length and for the correct position of the pen-arm spindle. When replacing the pen on the pen arm, or fitting a new pen arm, every care must be taken to ensure that the effective pen-arm length is correct. The displacement of the pen at the end of the pen arm for a given angular movement is proportional to the length of the pen arm, so that an error of 8 mm in the length of a pen arm which should be 160 mm long will give an error of 5 per cent in the deflexion of the pen, and in the scale value on the chart at that point. The correct charts for all standard Meteorological Office instruments have identifying numbers, and these should always be quoted when

requesting stocks. If a non-standard chart has to be supplied specially, the data given should include the length of the pen arm and the position of the pen-arm axis, if the hour lines are not straight.

Pens. Various types of pen are used on the standard Meteorological Office instruments; the chief ones are illustrated in Figure A2. The type in normal use on the commoner instruments is shown at (a); it consists of a simple triangular reservoir attached to a short holder which can be slid over the end of the pen arm; it can hold more than sufficient ink for at least a normal week's record on any standard sized drum. Preferred alternatives for use on certain instruments are shown in (b) for the tilting-siphon rain-gauge, and in (c) for the thermograph and barograph. Both (b) and (c) are disposable items consisting of an ink reservoir fitted with a fibre nib; either pen will provide at least a year's normal record.

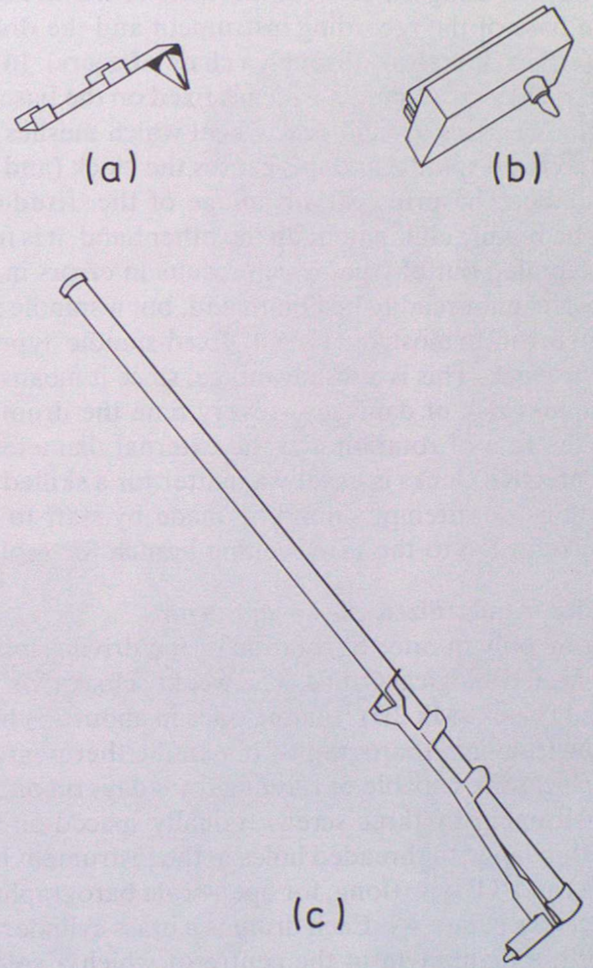

Figure A2. Instrument pens.

A.1.4 Electrosensitive paper

Recorders using various types of electrosensitive paper are also used. Paper is coated with zinc oxide so that when a small current passes from a stylus to the paper the zinc oxide coating is reduced to free zinc and a marking results. This process produces a fine, clean and dry trace resistant to smudging.

A.1.5 Electrical recorders

Devices for balancing potentiometric or bridge recorders have various forms, some manual, some self-balancing. Whatever the method used the principle is the same. A galvanometer, or an electronic circuit, is arranged to detect when the system is out of balance. Where a galvanometer is used, the position of the galvanometer pointer is detected either manually or electrically, and the slide-wire contact moved to the point of balance. Where an electronic circuit is used to detect the out-of-balance it is usual for the output of the detecting circuit to control the direction of rotation of a reversible motor which moves the slide-wire contact and positions the pen arm or pointer.

A.1.6 Clocks, drums and time-scales

Most meteorological recording instruments are fitted with 'daily' or 'weekly' clocks, i.e. clocks which cause the drum to rotate once in about 25½ hours and once in about 7⅓ days respectively. The overlap is necessary to allow some margin for the time of changing the chart, and to prevent the trace from crossing the join when the pen is near the top or bottom of the chart (on those instruments in which the hour lines are curved).

There are two possible ways of using the clock to drive the drum. In the 'fixed-clock' type the clock is screwed to the base of the recording instrument and the drum attached to the main spindle of the clock (either directly or through a chain of gears). In the 'fixed-spindle' type the clock is supported on a central spindle which is fixed on the base of the instrument. The main spindle of the clock carries a small gear wheel which meshes with another gear wheel rigidly attached to the fixed spindle and this causes the clock (and attached drum) to rotate round the fixed spindle. The principal advantage of the 'fixed-clock' type is that backlash in the system can be readily eliminated; on the other hand, it is found that the main spindle of the clock can be pulled out of true, which results in errors in the record. In the 'fixed-spindle' type backlash cannot readily be eliminated, but a spindle slightly out of true does not result in significant error. In most, but not all, 'fixed-spindle' type clocks the drum is permanently attached to the clock. This is a disadvantage, since it means that the clock will be handled — with consequent risk of damage — every time the drum is removed.

Time-scales depend on the rate of rotation and the external diameter of the drum.

The repair of faulty or defective clocks is usually a matter for a skilled clock repairer. At Meteorological Office stations no attempt should be made by staff to repair a defective clock; the clock should be returned to the provisioning branch for replacement.

A.1.7 Meteorological Office standardized clocks and drums

Two 'fixed' clocks differing only in rates of rotation of the driving spindles, serve as the standardized clocks of the Meteorological Office. The weekly clock (Mk 2A) rotating once in about 7⅓ days and the daily clock (Mk 2B) rotating once in about 25½ hours are used with the commoner recording instruments (barographs, bimetallic thermographs, hygrographs and rain recorders). Both clocks are capable of running for 8 days on one full winding. The clock is attached to the instrument by three screws, equally spaced on a circle of 89 mm diameter, passing through the flange to threaded holes in the instrument base. Two standardized drums, 'S' type (short) and 'O' type (long, for open-scale barographs), are for use with either of the standardized clocks (Plate A). Each drum is a brass cylinder, of defined height and diameter, provided with a diaphragm in the centre of which a collar is screwed and through which the clock's driving spindle passes. The collar has radial teeth on its underside which engage with similar teeth on a collar attached to a clutch drive on the driving spindle of the clock; a knurled nut secures the drum to the driving spindle of the clock. The object of the clutch drive is to facilitate the setting of the drum to its correct position when fitted to the clock. The drum is flanged around its base and the chart is held in position by two clips. In addition to the chart clips the 'O' type drum has two small pins screwed into its side, lying in the same line as the chart clips. These pins help to keep the chart in position where the two ends overlap. The 'S' type is 93 mm in diameter, so that it gives a time-scale of 11.4 mm h^{-1} with a daily clock. When used with a weekly clock Mk 2A the clock is adjusted to rotate once in 7 days 7.2 hours, giving a time-scale of 1.67 mm h^{-1}. The 'O' type drum is not normally used with a daily clock, but if it were the time-scale would be 17.2 mm h^{-1}. Used with a weekly clock Mk 2A, the clock is adjusted to rotate once in 7 days 8 hours, giving a time-scale of 2.5 mm h^{-1}. (The difference between a time of rotation of 7 days 8 hours and 7 days 7.2 hours is negligible for most purposes.) The standardized clocks and drums are completely

Plate A. Standard Meteorological Office clocks and drums.

interchangeable, i.e. any clock can be used with any drum. The weekly clocks can be regulated over a range of 2¼ hours in the 7 days and the daily clock over a range of 20 minutes in the 24 hours.

A.2 CORRECTION OF RECORDING INSTRUMENTS

It is important to ensure correct timing of any part of the recorded trace, and to be able to make an estimate of any errors in the record itself. There are three main causes of error that can affect the timing of the record:

(a) Backlash between the drum and the spindle on which it is mounted. This defect is not serious with clocks of the standard Meteorological Office pattern or similar types. It delays the starting of the record and causes a constant error once the record has started.

(b) An error in the clock rate (or the use of an unsuitable time-scale on the chart). If the difference is small the rate of revolution of the drum can be adjusted to the correct value (given by the time-scale on the chart) by means of the clock regulator. Small errors may occur, however, owing to the variability of the clock rate, e.g. with temperature changes.

(c) Errors due to the change in length of the chart with humidity variations (see page A–3). These are small in charts which are cut from the paper in the correct direction, but are serious if the chart is cut in the wrong direction.

In order that errors of this kind may be recognized it is essential to make accurate time marks on the records themselves. Although it is preferable that the time marks be made at about the same time each day, it is not essential provided the exact time at which the mark is made is known. The actual time (it suffices for most records if it is correct to the nearest minute) should be entered in the register. On weekly charts one time mark a day would suffice. On daily charts it is preferable to have more than one, the first being made at least half an hour but not more than 2 hours after starting the record, and another after about a further 8–12 hours. It is often convenient to make a time mark coincide with an hour mark and to note the timing error.

On most instruments a time mark may be made by depressing the pen between 3 mm and 6 mm and then releasing it. These limits should not be exceeded, as the careless depression of the pen can often disturb the calibration of the instrument or even strain some of the parts beyond their elastic limits.

On some instruments, e.g. barographs, a simple mechanical device is provided which enables time marks to be made without opening the case of the instrument. If a reading of the record has to be obtained at the same time as the time mark it should be made just before the time mark and not after it.

Recording instruments are generally less accurate than the comparable indicating instruments, and they cannot often be made absolute. It is therefore usual to compare their readings with those of an indicating instrument at several of the main observation hours throughout the day. In some recording instruments, e.g. the barograph, this will give immediately the error of the record or the necessary correction to the record, assuming that the indicating instrument is correct. It should be noted that the error is equal, but opposite in sign, to the correction. The mean correction for the day can therefore be ascertained and applied to any tabulated readings taken from the record.

No instrument responds immediately to changes in the element that is being measured, and different instruments respond at different rates. Comparisons should therefore be made only when the measured element is constant or changing very slowly, or mean values should be taken over a period in which any errors due to the different time-constants may be expected to cancel out.

Another possible procedure is to plot the readings of the recording and indicating instruments against one another; the points obtained should lie on or about a line at 45° to each axis passing through the origin. If the best-fitting straight line does not pass through the origin a zero error is indicated, and if the slope is not 45° there is an error in the scale value of one instrument, usually the recording instrument.

A.3. OPERATIONAL PROCEDURE

Some general instructions on the method of handling recording instruments are given below. These are supplementary to the more particular instructions given for each individual instrument.

A.3.1 Changing the chart

Remove the pen from the old chart, noting the correct time to the nearest minute (this serves as an extra time mark). Clean the pen if necessary and top with ink. See that the ink is flowing sufficiently freely to give a legible trace, but not so freely as to give a thick trace. It is rarely advisable to fill the reservoir completely. Remove the old chart and wrap the new chart round the drum so that it fulfils the following conditions (these are absolutely necessary if good and reliable records are to be obtained):

(a) The chart should fit tightly round the drum.
(b) The lines of equal scale value should be parallel to the flange at the bottom of the drum, i.e. corresponding lines on the beginning and end of the chart in the overlap portion should coincide.
(c) The bottom of the chart should be as close to the flange as possible and touching it in at least one place (if the chart is not cut quite correctly it may not be possible for it to touch the flange in all places and still comply with the other conditions cited).
(d) The end of the chart should overlap the beginning and not vice versa.

When the chart is fitted properly the spring clips should hold it in place. The clock can then be wound and the new record started. When setting the pen to the correct time the final adjustment should be made by moving the drum in the opposite direction to its normal motion to take up any backlash in the gear train, i.e. the drum should be moved from a time on the chart in advance of the actual time back to its correct position. Once they have been correctly set most recording instruments should not require readjustment more often than three or four times a year. If careful examination, extending over a period, shows that readjustment is necessary this may be done at the time a chart is changed, and a note should be made on the chart and in the register.

A.3.2 Writing up the chart

Before being filed away, the record should have inserted on it the following particulars: date (including the year), name of the station, its position, its height above mean sea level, actual time of each of the time marks, readings of the control instruments when the time marks were made, and time at which the record began and ended. If a reliable estimate of the mean errors in the record has been made, covering the period of the chart, this should be indicated. The reasons for any abnormal features, e.g. failure to ink, clock stopping, etc., should also be recorded if known.

A.3.3 Care at each main observation hour

See that the instrument is recording properly and read it. If necessary, a time mark should be made.

A.3.4 General hints (including cleaning)

Special care should always be taken to keep instruments clean. This not only improves their performance (by reducing friction) but also lengthens their useful life (by preventing corrosion) and improves their appearance. General methods of cleaning the different materials most often used in instruments are as follows:

(a) *Plain brass or copper parts*. Unlacquered brass or copper parts may be kept bright by the use of jeweller's rouge applied with an oily rag or by metal polish applied sparingly. The polish should not be allowed to reach any bearing surfaces. The inside of a rain-gauge funnel should however only be rubbed with a dry rag.
(b) *Lacquered brass or copper parts*. These should be cleaned with a soft chamois leather. No polish should be applied, but where there is exposure to damp a little petroleum jelly may be used with advantage.
(c) *Polished woodwork*. This should be cleaned with a soft chamois-leather. A little linseed oil may be rubbed in with a soft cloth if necessary.
(d) *Glass and porcelain*. The dirt should be cleaned off with a moist rag or chamois-leather.
(e) *Bearings, pinions and hinges of instrument cases*. These should be lubricated sparingly with a touch of clock oil. Refer also to the detailed instructions for the instrument.
(f) *Ball races*. These should be treated in accordance with the detailed instructions for each instrument.
(g) *Steel parts*. These should be cleaned with an oily rag and protected from rust with a trace of petroleum jelly. If, in spite of care, rust appears, the part should be carefully cleaned with a fine emery cloth or carborundum cloth.
(h) *Painted woodwork*. In dusty localities woodwork should be brushed periodically, and at stations affected by smoke or soot a thorough cleaning with soap and water should be carried out once a month.
(i) *Painted surfaces liable to inking*. The ink should be removed while wet with a damp cloth. Older stains should be removed by the application of a small quantity of whiting applied with a damp cloth. Methylated spirit may be used with the whiting if there is no risk of this getting on to lacquered brass or polished woodwork.
(j) Naphthalene balls are effective in keeping insects from the interior of instruments exposed out of doors, e.g. recording rain-gauges.

Special care must be given to keeping the end of the pen arm and the fitting which actually supports the pen free from ink, or else corrosion may set in. This may lead to the use of a pen arm which is too short and thus give rise to faulty records.

APPENDIX 2

The International Systems of units (SI)

The International System (SI) consists of seven 'base units' together with two 'supplementary units'. From these are formed others known as 'derived units'. The base and supplementary units, and some of the derived units, have been given names and symbols. The symbols are printed in lower case except where derived from the name of a person; for example m (metre), but A (ampere). Symbols are not pluralized (1 m, 10 m) nor do they take a full stop. The names of the units do not, however, take capitals (except of course at the beginning of a sentence), although they may be pluralized; for example, 1 kelvin, 10 kelvins.

The *base units* are:

metre (symbol m)	the unit of length
kilogram (symbol kg)	the unit of mass
second (symbol s)	the unit of time
ampere (symbol A)	the unit of electrical current
kelvin (symbol K)	the unit of thermodynamic temperature, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
candela (symbol cd)	the unit of luminous intensity
mole (symbol mol)	the unit of the amount of a substance which contains the same number of molecules as there are atoms in exactly 12 grams of pure carbon.

The two *supplementary units* are:

radian (symbol rad)	the measure of a plane angle
steradian (symbol sr)	the measure of a solid angle.

A few of the *derived units* are:

Quantity	*Name of unit*	*Symbol*	*Expressed in base units*
frequency	hertz	Hz	$1\ \text{Hz} = 1\ \text{s}^{-1}$
force	newton	N	$1\ \text{N} = 1\ \text{kg m s}^{-2}$
pressure	pascal	Pa	$1\ \text{Pa} = 1\ \text{N m}^{-2}$
work	joule	J	$1\ \text{J} = 1\ \text{N m}$
power	watt	W	$1\ \text{W} = 1\ \text{J s}^{-1}$

(1 newton = 10^5 dynes, 1 pascal = 10^{-2} millibars, 1 joule = 10^7 ergs.)

Multiplying prefixes

The multiples and sub-multiples of the units are not arbitrarily related to the units, as is usual in the British system,

e.g. 1 pound = 16 ounces = 7000 grains

1 yard = 3 feet = 36 inches,

but are formed by means of multiplying prefixes which are the same irrespective of the unit to which they are applied.

The names and values of the prefixes, and some examples of their use, are given below. Because the prefixes cover such an astronomical range it is not normally necessary to consider more than a selection of them applied to any one unit.

Prefix name	*Prefix symbol*	*Factor by which the unit is multiplied*	
tera	T	10^{12} =	1 000 000 000 000
giga	G	10^{9} =	1 000 000 000
mega	M	10^{6} =	1 000 000
kilo	k	10^{3} =	1000
hecto	h	10^{2} =	100
deca	da	10^{1} =	10
deci	d	10^{-1} =	0.1
centi	c	10^{-2} =	0.01
milli	m	10^{-3} =	0.001
micro	μ	10^{-6} =	0.000 001
nano	n	10^{-9} =	0.000 000 001
pico	p	10^{-12} =	0.000 000 000 001
femto	f	10^{-15} =	0.000 000 000 000 001
atto	a	10^{-18} =	0.000 000 000 000 000 001

Examples:

gigahertz (GHz), megawatt (MW), kilometre (km), centimetre (cm), milligram (mg), microsecond (μs), nanometre (nm), picofarad (pF).

NON-SI UNITS

The following non-SI units are in current use in the Meteorological Office and may be found in publications of the Office.

1. **Pressure**

The millibar is used as the unit of pressure in meteorology. Despite the recommended abbreviation mbar, the Meteorological Office will continue to use mb (1 mb = 1 hPa, where h = hecto = 10^2). The WMO preferred unit is the hPa, though it has yet to be promulgated.

2. **Temperature**

The unit degree Celsius (symbol °C) continues to be used.

Celsius temperature = temperature (in kelvins) minus 273.15 K (note that the sign ° is no longer used with K).

3. **Distance**

There is a continuing requirement for some distances to be measured in nautical miles (symbol n. mile).

Because the nautical mile varies with latitude, an internationally agreed International Nautical Mile is preferred. This has been in use in the United Kingdom since 1970.

The International Nautical Mile is defined as 1852 m (6076.12 feet).

4. **Height**

Heights other than cloud heights are expressed in metres. Because of the requirements of aviation the heights of cloud will continue for the time being to be expressed in feet (1 foot = 0.3048 m).

5. **Speed**

The derived SI unit is the metre per second (m s^{-1}). However, the World Meteorological Organization recommends the use of the knot for horizontal wind speed for the time being (1 knot = 1 nautical mile per hour $\approx 0.5\ \text{m s}^{-1}$). The symbol kn for knot is recommended to avoid confusion with the symbol for kilotonne and will be used in Meteorological Office publications.

6. **Time**

Units other than SI, such as day, week, month and year, are in common use.

7. **Direction**

Direction is measured in degrees clockwise from north and refers to the true compass.

8. **Cloud amounts**

The use of 'okta' (one eighth of the area of the sky) for the measurement of cloud amount is authorized by the World Meteorological Organization.

APPENDIX 3

Terminology

In metrology (the field of knowledge concerned with measurement) confusion often arises in the usage of terms. These differences may range from subtle changes of meaning of common terms to the misuse of everyday terms, extracted from dictionaries, by ascribing to them specific meanings applicable only in certain areas of use.

Whilst by no means comprehensive, the following list represents terms occurring most frequently in this volume. For a more complete glossary of terms reference should be made to British Standards Institution publication BS 5233 from which these definitions are extracted.

Accuracy (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give indications equivalent to the true value of the quantity measured. The quantitative expression of this concept should be in terms of uncertainty.

Analogue (measuring) instrument. Measuring instrument in which the indication is a continuous function of the corresponding value of the quantity to be measured, e.g. mercury-in-glass thermometer.

Calibration. All the operations for the purpose of determining the values of the errors of a measuring instrument.

Conventional true value (of a quantity). A value approximating to the true value of a quantity such that, for the purpose for which that value is used, the difference between these two values can be neglected.

Correction. A value which must be added algebraically to the indicated value (uncorrected result) of a measurement to obtain the measured value (corrected result).

Detector. A device or substance which responds to the presence of a particular quantity without necessarily measuring the value of that quantity.

Digital (measuring) instrument. Measurement instrument in which the quantity to be measured is accepted as, or is converted into, coded discrete signals and provides an output and/or display in digital form.

Discrimination (of a measuring instrument). The property which characterizes the ability of a measuring instrument to respond to small changes of the quantity measured. *Note*. In some fields of measurement the term 'resolution' is used as synonymous with 'discrimination', but attention is drawn to 'sensitivity'.

Error (of indication, or of response) *of a measuring instrument*. The difference $v_i - v_c$ between the value indicated by (or the response of) the measuring instrument v_i and the conventional true value of the measured quantity v_c.

Hysteresis (of a measuring instrument). That property of a measuring instrument whereby it gives different indications, or responses, for the same value of the measured quantity, according to whether that value has been reached by a continuously increasing change or by a continuously decreasing change of that quantity.

Index. A fixed or movable part of the indicating device (e.g. recording pen, a pointer) whose position with reference to the scale marks enables the indicated value to be observed.

Indicating instrument. Measuring instrument which is intended to give, by means of a single unique observation, the value of a measured quantity at the time of that observation. An indicating instrument may have either continuous or discontinuous variation of indication.

Indication (or *response*) *of a measuring instrument*. The value of the quantity measured, as indicated or otherwise provided by a measuring instrument.

Maximum permissible error (of a measuring instrument). The extreme values of the error (positive or negative) permitted by specifications, regulations etc., for a measuring instrument.

Quantity (measurable). An attribute of a phenomenon or a body which may be distinguished qualitatively and determined quantitatively.

Range (of a measuring instrument). The interval between the lower and upper range-limits, e.g. a thermometer may have a range −40 °C to +60 °C.

Repeatability (of measurement). A quantitative expression of the closeness of successive measurements of the same value of the same quantity carried out by the same method, by the same observer, with the same measuring instruments, at the same location at appropriately short intervals of time.

Repeatability (of a measuring instrument). The quality which characterizes the ability of a measuring instrument to give identical indications, or responses, for repeated applications of the same value of the measured quantity under stated conditions of use.

Reproducibility (of measurement). The quantitative expression of the closeness of the agreement between the results of measurements of the same value of the same quantity, where the individual measurements are made under different defined conditions, e.g. by different methods, with different measuring instruments.

Resolution. See *Discrimination*.

Response. See *Indication*.

Response time (of a measuring instrument).* The time which elapses after a step change in the quantity measured, up to the point at which the measuring instrument gives an indication equal to the expected indication corresponding to the new value of the quantity, or not differing from this by more than a specified amount.

Scale. The array of indicating marks, together with any associated figuring, in relation to which the position of an index is observed. The term is frequently extended to include the surface which carries the marks or figuring.

Sensitivity (of a measuring instrument). (a) The relationship of the change of the response to the corresponding change of the stimulus (it is normally expressed as a quotient), or (b) the value of the stimulus required to produce a response exceeding, by a specified amount, the response already present due to other causes, e.g. noise.

Sensor. The part of a measuring instrument which responds directly to the measured quantity.

Span. The algebraic difference between the upper and lower values specified as limiting the range of operation of a measuring instrument, e.g. a thermometer intended to measure over the range −40 °C to +60 °C has a span of 100 °C.

Standard. A measuring instrument, or measuring apparatus, which defines, represents physically, conserves or reproduces the unit of measurement of a quantity (or a multiple or sub-multiple of that unit) in order to transmit it to other measuring instruments by comparison.

Primary standard. A standard of a particular quantity which has the highest class of metrological qualities in a given field.

Secondary standard. A standard the value of which is determined by direct or indirect comparison with a primary standard.

Reference standard. A standard, generally the best available at a location, from which the measurements made at the location are derived.

Working standard. A measurement standard, not specifically reserved as a reference standard, which is intended to verify measuring instruments of lower accuracy.

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*For the purposes of this handbook, where a response time is quoted it refers to the time necessary for a measuring instrument to register 90 per cent of a step change in the quantity being measured. The time taken to register 63.2 per cent of a change is given the preferred title 'time-constant'.

Transfer standard. A measuring device used to compare measurement standards, or to compare a measuring instrument with a measurement standard by sequential comparison.

Travelling standard. A measuring device, sometimes of special construction, used for the comparison of values of a measured quantity at different locations.

Systematic error. An error which, in the course of a number of measurements of the same value of a given quantity, remains constant when measurements are made under the same conditions and remains constant or varies according to a definite law when the conditions change.

Transducer (measuring). A device which serves to transform, in accordance with an established relationship, the measured quantity (or a quantity already transformed therefrom) into another quantity or into another value of the same quantity, with a specified accuracy, and which may be used separately as a complete unit.

Uncertainty of measurement. That part of the expression of the result of a measurement which states the range of values within which the true value or, if appropriate, the conventional true value is estimated to lie.

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