CHAPTER 10

MEASUREMENT OF EVAPORATION

10.1 GENERAL

10.1.1 Definitions

The *International Glossary of Hydrology* (WMO/UNESCO, 1992) and the *International Meteorological Vocabulary* (WMO, 1992) present the following definitions (but note some differences):

(Actual) evaporation: Quantity of water evaporated from an open water surface or from the ground.

Transpiration: Process by which water from vegetation is transferred into the atmosphere in the form of vapour.

(Actual) evapotranspiration (or *effective evapotranspiration*)*:* Quantity of water vapour evaporated from the soil and plants when the ground is at its natural moisture content.

Potential evaporation (or *evaporativity*)*:* Quantity of water vapour which could be emitted by a surface of pure water, per unit surface area and unit time, under existing atmospheric conditions.

Potential evapotranspiration: Maximum quantity of water capable of being evaporated in a given climate from a continuous expanse of vegetation covering the whole ground and well supplied with water. It includes evaporation from the soil and transpiration from the vegetation from a specific region in a specific time interval, expressed as depth of water.

If the term *potential evapotranspiration* is used, the types of evaporation and transpiration occurring must be clearly indicated. For more details on these terms refer to WMO (1994).

10.1.2 Units and scales

The rate of evaporation is defined as the amount of water evaporated from a unit surface area per unit of time. It can be expressed as the mass or volume of liquid water evaporated per area in unit of time, usually as the equivalent depth of liquid water evaporated per unit of time from the whole area. The unit of time is normally a day. The amount of evaporation should be read in millimetres (WMO, 2003). Depending on the type of instrument, the usual measuring accuracy is 0.1 to 0.01 mm.

10.1.3 Meteorological requirements

Estimates both of evaporation from free water surfaces and from the ground and of evapotranspiration from vegetation-covered surfaces are of great importance to hydrological modelling and in hydrometeorological and agricultural studies, for example, for the design and operation of reservoirs and irrigation and drainage systems.

Performance requirements are given in Part I, Chapter 1. For daily totals, an extreme outer range is 0 to 100 mm, with a resolution of 0.1 mm. The uncertainty, at the 95 per cent confidence level, should be ±0.1 mm for amounts of less than 5 mm, and ±2 per cent for larger amounts. A figure of 1 mm has been proposed as an achievable accuracy. In principle, the usual instruments could meet these accuracy requirements, but difficulties with exposure and practical operation cause much larger errors (WMO, 1976).

Factors affecting the rate of evaporation from any body or surface can be broadly divided into two groups, meteorological factors and surface factors, either of which may be rate-limiting. The meteorological factors may, in turn, be subdivided into energy and aerodynamic variables. Energy is needed to change water from the liquid to the vapour phase; in nature, this is largely supplied by solar and terrestrial radiation. Aerodynamic variables, such as wind speed at the surface and vapour pressure difference between the surface and the lower atmosphere, control the rate of transfer of the evaporated water vapour.

It is useful to distinguish between situations where free water is present on the surface and those where it is not. Factors of importance include the amount and state of the water and also those surface characteristics which affect the transfer process to the air or through the body surface. Resistance to moisture transfer to the atmosphere depends, for example, on surface roughness; in arid and semi-arid areas, the size and shape of the evaporating surface is also extremely important. Transpiration from vegetation, in addition to the meteorological and surface factors already noted, is largely determined by plant characteristics and responses. These include, for example, the number and size of stomata (openings in the leaves), and whether these are open or closed. Stomatal resistance to moisture transfer shows a diurnal response but is also considerably dependent upon the availability of soil moisture to the rooting system.

The availability of soil moisture for the roots and for the evaporation from bare soil depends on the capillary supply, namely, on the texture and composition of the soil. Evaporation from lakes and reservoirs is influenced by the heat storage of the water body.

Methods for estimating evaporation and evapotranspiration are generally indirect; either by point measurements by an instrument or gauge, or by calculation using other measured meteorological variables (WMO, 1997).

10.1.4 **Measurement methods**

Direct measurements of evaporation or evapotranspiration from extended natural water or land surfaces are not practicable at present. However, several indirect methods derived from point measurements or other calculations have been developed which provide reasonable results.

The water loss from a standard saturated surface is measured with evaporimeters, which may be classified as atmometers and pan or tank evaporimeters. These instruments do not directly measure either evaporation from natural water surfaces, actual evapotranspiration or potential evapotranspiration. The values obtained cannot, therefore, be used without adjustment to arrive at reliable estimates of lake evaporation or of actual and potential evapotranspiration from natural surfaces.

An evapotranspirometer (lysimeter) is a vessel or container placed below the ground surface and filled with soil, on which vegetation can be cultivated. It is a multi-purpose instrument for the study of several phases of the hydrological cycle under natural conditions. Estimates of evapotranspiration (or evaporation in the case of bare soil) can be made by measuring and balancing all the other water budget components of the container, namely, precipitation, underground water drainage, and change in water storage of the block of soil. Usually, surface runoff is eliminated. Evapotranspirometers can also be used for the estimation of the potential evaporation of the soil or of the potential evapotranspiration of plant-covered soil, if the soil moisture is kept at field capacity.

For reservoirs or lakes, and for plots or small catchments, estimates may be made by water budget, energy budget, aerodynamic and complementarity approaches. The latter techniques are discussed in section 10.5.

It should also be emphasized that different evaporimeters or lysimeters represent physically different measurements. The adjustment factors required for them to represent lake or actual or potential evaporation and evapotranspiration are necessarily different. Such instruments and their exposure should, therefore, always be described very carefully and precisely, in order to understand the measuring conditions as fully as possible.

More details on all methods are found in WMO (1994).

10.2 **ATMOMETERS**

10.2.1 **Instrument types**

An atmometer is an instrument that measures the loss of water from a wetted, porous surface. The wetted surfaces are either porous ceramic spheres, cylinders, plates, or exposed filter-paper discs saturated with water. The evaporating element of the livingstone atmometer is a ceramic sphere of about 5 cm in diameter, connected to a water reservoir bottle by a glass or metal tube. The atmospheric pressure on the surface of the water in the reservoir keeps the sphere saturated with water. The Bellani atmometer consists of a ceramic disc fixed in the top of a glazed ceramic funnel, into which water is conducted from a burette that acts as a reservoir and measuring device. The evaporating element of the Piche evaporimeter is a disc of filter paper attached to the underside of an inverted graduated cylindrical tube, closed at one end, which supplies water to the disc. Successive measurements of the volume of water remaining in the graduated tube will give the amount lost by evaporation in any given time.

10.2.2 **Measurement taken by atmometers**

Although atmometers are frequently considered to give a relative measure of evaporation from plant surfaces, their measurements do not, in fact, bear any simple relation to evaporation from natural surfaces.

Readings from Piche evaporimeters with carefully standardized shaded exposures have been used with some success to derive the aerodynamic term, a multiplication of a wind function and the saturation vapour pressure deficit, required for evaporation estimation by, for example, Penman's combination method after local correlations between them were obtained.

While it may be possible to relate the loss from atmometers to that from a natural surface empirically, a different relation may be expected for each type of surface and for differing climates. Atmometers are likely to remain useful in small-scale surveys. Their great advantages are their small size, low cost and small water requirements. Dense networks of atmometers can be installed over a small area for micrometeorological studies. The use of atmometers is not recommended for water resource surveys if other data are available.

10.2.3 **Sources of error in atmometers**

One of the major problems in the operation of atmometers is keeping the evaporating surfaces clean. Dirty surfaces will affect significantly the rate of evaporation, in a way comparable to the wet bulb in psychrometry.

Furthermore, the effect of differences in their exposure on evaporation measurements is often remarkable. This applies particularly to the exposure to air movement around the evaporating surface when the instrument is shaded.

10.3 **EVAPORATION PANS AND TANKS**

Evaporation pans or tanks have been made in a variety of shapes and sizes and there are different modes of exposing them. Among the various types of pans in use, the United States Class A pan, the Russian GGI-3000 pan and the Russian 20 m^2 tank are described in the following subsections. These instruments are now widely used as standard network evaporimeters and their performance has been studied under different climatic conditions over fairly wide ranges of latitude and elevation. The pan data from these instruments possess stable, albeit complicated and climate-zone-dependent, relationships with the meteorological elements determining evaporation, when standard construction and exposure instructions have been carefully followed. The adoption of the Russian 20 m^2 tank as the international reference evaporimeter has been recommended.

10.3.1 **United States Class A pan**

The United States Class A pan is of cylindrical design, 25.4 cm deep and 120.7 cm in diameter. The bottom of the pan is supported 3 to 5 cm above the ground level on an open-frame wooden platform, which enables air to circulate under the pan, keeps the bottom of the pan above the level of water on the ground during rainy weather, and enables the base of the pan to be inspected without difficulty. The pan itself is constructed of 0.8 mm thick galvanized iron, copper or monel metal, and is normally left unpainted. The pan is filled to 5 cm below the rim (which is known as the reference level).

The water level is measured by means of either a hookgauge or a fixed-point gauge. The hookgauge consists of a movable scale and vernier fitted with a hook, the point of which touches the water surface when the gauge is correctly set. A stilling well, about 10 cm across and about 30 cm deep, with a small hole at the bottom, breaks any ripples that may be present in the tank, and serves as a support for the hookgauge during an observation. The pan is refilled whenever the water level, as indicated by the gauge, drops by more than 2.5 cm from the reference level.

10.3.2 **Russian GGI-3000 pan**

The Russian GGI-3000 pan is of cylindrical design, with a surface area of 3 000 cm^2 and a depth of 60 cm. The bottom of the pan is cone-shaped. The pan is set in the soil with its rim 7.5 cm above the ground. In the centre of the tank is a metal index tube upon which a volumetric burette is set when evaporation observations are made. The burette has a valve, which is opened to allow its water level to equalize that in the pan. The valve is then closed and the volume of water in the burette is accurately measured. The height of the water level above the metal index tube is determined from the volume of water in, 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 should be maintained so that it does not fall more than 5 mm or rise more than 10 mm above the needle point. A GGI-3000 raingauge with a collector that has an area of 3 000 cm^2 is usually installed next to the GGI-3000 pan.

10.3.3 RUSSIAN 20 M^2 TANK

This tank has a surface of 20 m^2 and a diameter of about 5 m; it is cylindrical with a flat bottom and is 2 m deep. It is made of 4 to 5 mm thick welded iron sheets and is installed in the soil with its rim 7.5 cm above the ground. The inner and exposed outer surfaces of the tank are painted white. The tank is provided with a replenishing vessel and a stilling well with an index pipe upon which the volumetric burette is set when the water level in the tank is measured. 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. The water level should always be maintained so that it does not fall more than 5 mm below or rise more than 10 mm above the needle point. A graduated glass tube attached laterally to the replenishing tank indicates the amount of water added to the tank and provides a rough check of the burette measurement.

10.3.4 Measurements taken by evaporation pans and tanks

The rate of evaporation from a pan or tank evaporimeter is measured by the change in level of its free water surface. This may be done by such devices as described above for Class A pans and GGI-3000 pans.

Several types of automatic evaporation pans are in use. The water level in such a pan is kept constant by releasing water into the pan from a storage tank or by removing water from the pan when precipitation occurs. The amount of water added to, or removed from, the pan is recorded. In some tanks or pans, the level of the water is also recorded continuously by means of a float in the stilling well. The float operates a recorder.

Measurements of pan evaporation are the basis of several techniques for estimating evaporation and evapotranspiration from natural surfaces whose water loss is of interest. Measurements taken by evaporation pans are advantageous because they are, in any case, the result of the impact of the total meteorological variables, and because pan data are available immediately and for any period required. Pans are, therefore, frequently used to obtain information about evaporation on a routine basis within a network.

10.3.5 Exposure of evaporation pans and tanks

Three types of exposures are mainly used for pans and tanks as follows:

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

Evaporation stations should be located at sites that are fairly level and free from obstructions such as trees, buildings, shrubs or instrument shelters. Such single obstructions, when small, should not be closer than 5 times their height above the pan; for clustered obstructions, this becomes 10 times. Plots should be sufficiently large to ensure that readings are not influenced by spray drift or by upwind edge effects from a cropped or otherwise different area. Such effects may extend to more than 100 m. The plot should be fenced off to protect the instruments and to prevent animals from interfering with the water level; however, the fence should be constructed in such a way that it does not affect the wind structure over the pan.

The ground cover at the evaporation station should be maintained as similar as possible to the natural cover common to the area. Grass, weeds, and the like should be cut frequently to keep them below the level of the pan rim with regard to sunken pans (7.5 cm). Preferably this same grass height of below 7.5 cm applies also to Class A pans. Under no circumstance should the instrument be placed on a concrete slab or asphalt, or on a layer of crushed rock. This type of evaporimeter should not be shaded from the sun.

10.3.6 Sources of error in evaporation pans and tanks

The mode of pan exposure leads both to various advantages and to sources of measurement errors.

Pans installed above the ground are inexpensive and easy to install and maintain. They stay cleaner than sunken tanks as dirt does not, to any large extent, splash or blow into the water from the surroundings. Any leakage that develops after installation is relatively easy to detect and rectify. However, the amount of water evaporated is greater than that from sunken pans, mainly because of the additional radiant energy intercepted by the sides. Adverse side-wall effects can be largely eliminated by using an insulated pan, but this adds to the cost, would violate standard construction instructions and would change the "stable" relations mentioned in section 10.3.

Sinking the pan into the ground tends to reduce objectionable boundary effects, such as radiation on the side walls and heat exchange between the atmosphere and the pan itself. But the disadvantages are as follows:

(a) More unwanted material collects in the pan, with the result that it is difficult to clean;
(b) Leaks cannot easily be detected and rectified;
(c) The height of the vegetation adjacent to the pan is somewhat more critical. Moreover, appreciable heat exchange takes place between the pan and the soil, and this depends on many factors, including soil type, water content and vegetation cover.

A floating pan approximates more closely evaporation from the lake than from an onshore pan exposed either above or at ground level, even though the heat-storage properties of the floating pan are different from those of the lake. It is, however, influenced by the particular lake in which it floats and it is not necessarily a good indicator of evaporation from the lake. Observational difficulties are considerable and, in particular, splashing frequently renders the data unreliable. Such pans are also costly to install and operate.

In all modes of exposure it is most important that the tank should be made of non-corrosive material and that all joints be made in such a way as to minimize the risk of the tank developing leaks.

Heavy rain and very high winds are likely to cause splash-out from pans and may invalidate the measurements.

The level of the water surface in the evaporimeter is important. If the evaporimeter is too full, as much as 10 per cent (or more) of any rain falling may splash out, leading to an overestimate of evaporation. Too low a water level will lead to a reduced evaporation rate (of about 2.5 per cent for each centimetre below the reference level of 5 cm, in temperate regions) due to excessive shading and sheltering by the rim. If the water depth is allowed to become very shallow, the rate of evaporation rises due to increased heating of the water surface.

It is advisable to restrict the permitted water-level range either by automatic methods, by adjusting the level at each reading, or by taking action to remove water when the level reaches an upper-limit mark, and to add water when it reaches a lower-limit mark.

10.3.7 Maintenance of evaporation pans and tanks

An inspection should be carried out at least once a month, with particular attention being paid to the detection of leaks. The pan should be cleaned out as often as necessary to keep it free from litter, sediment, scum and oil films. It is recommended that a small amount of copper sulphate, or of some other suitable algacide, be added to the water to restrain the growth of algae.

If the water freezes, all the ice should be broken away from the sides of the tank and the measurement of the water level should be taken while the ice is floating. Provided that this is done, the fact that some of the water is frozen will not significantly affect the water level. If the ice is too thick to be broken the measurement should be postponed until it can be broken, the evaporation should then be determined for the extended period.

It is often necessary to protect the pan from birds and other small animals, particularly in arid and tropical regions. This may be achieved by the use of the following:

(a) Chemical repellents: In all cases where such protection is used, care must be taken not to change significantly the physical characteristics of the water in the evaporimeter;
(b) A wire-mesh screen supported over the pan: Standard screens of this type are in routine use in a number of areas. They prevent water loss caused by birds and animals, but also reduce the evaporation loss by partly shielding the water from solar radiation and by reducing wind movement over the water surface. In order to obtain an estimate of the error introduced by the effect of the wire-mesh screen on the wind field and the thermal characteristics of the pan, it is advisable to compare readings from the protected pan with those of a standard pan at locations where interference does not occur. Tests with a protective cylinder made of 25 mm hexagonal-mesh steel wire netting supported by an 8 mm steel-bar framework showed a consistent reduction of 10 per cent in the evaporation rate at three different sites over a two-year period.

10.4 EVAPOTRANSPIROMETERS (LYSIMETERS)

Several types of lysimeters have been described in the technical literature. Details of the design of some instruments used in various countries are described in WMO (1966; 1994).

In general, a lysimeter consists of the soil-filled inner container and retaining walls or an outer container, as well as special devices for measuring percolation and changes in the soil-moisture content.

There is no universal international standard lysimeter for measuring evapotranspiration. The surface area of lysimeters in use varies from 0.05 to some 100 m^2 and their depth varies from 0.1 to 5 m. According to their method of operation, lysimeters can be classified into non-weighable and weighable instruments. Each of these devices has its special merits and drawbacks, and the choice of any type of lysimeter depends on the problem to be studied.

Non-weighable (percolation-type) lysimeters can be used only for long-term measurements, unless the soil-moisture content can be measured by some independent and reliable technique. Large-area percolation-type lysimeters are used for water budget and evapotranspiration studies of tall, deep-rooting vegetation cover, such as mature trees. Small, simple types of lysimeters in areas with bare soil or grass and crop cover could provide useful results for practical purposes under humid conditions. This type of lysimeter can easily be installed and maintained at a low cost and is, therefore, suitable for network operations.

Weighable lysimeters, unless of a simple micro-lysimeter-type for soil evaporation, are much more expensive, but their advantage is that they secure reliable and precise estimates of short-term values of evapotranspiration, provided that the necessary design, operation and siting precautions have been taken.

Several weighing techniques using mechanical or hydraulic principles have been developed. The simpler, small lysimeters are usually lifted out of their sockets and transferred to mechanical scales by means of mobile cranes. The container of a lysimeter can be mounted on a permanently installed mechanical scale for continuous recording. The design of the weighing and recording system can be considerably simplified by using load cells with strain gauges of variable electrical resistance. The hydraulic weighing systems use the principle of fluid displacement resulting from the changing buoyancy of a floating container (so-called floating lysimeter), or the principle of fluid pressure changes in hydraulic load cells.

The large weighable and recording lysimeters are recommended for precision measurements in research centres and for standardization and parameterization of other methods of evapotranspiration measurement and the modelling of evapotranspiration. Small weighable types of lysimeters are quite useful and suitable for network operation. Microlysimeters for soil evaporation are a relatively new phenomenon.

10.4.1 Measurements taken by lysimeters

The rate of evapotranspiration may be estimated from the general equation of the water budget for the lysimeter containers. Evapotranspiration equals precipitation/irrigation minus percolation minus change in water storage.

Hence, the observational programme on lysimeter plots includes precipitation/irrigation, percolation and change in soil water storage. It is useful to complete this programme through observations of plant growth and development.

Precipitation – and irrigation, if any – is preferably measured at ground level by standard methods. Percolation is collected in a tank and its volume may be measured at regular intervals or recorded. For precision measurements of the change in water storage, the careful gravimetric techniques described above are used. When weighing, the lysimeter should be sheltered to avoid wind-loading effects.

The application of the volumetric method is quite satisfactory for estimating long-term values of evapotranspiration. With this method, measurements are taken of the amount of precipitation and percolation. It is assumed that a change in water storage tends to zero over the period of observation. Changes in the soil moisture content may be determined by bringing the moisture in the soil up to field capacity at the beginning and at the end of the period.

10.4.2 Exposure of evapotranspirometers

Observations of evapotranspiration should be representative of the plant cover and moisture conditions of the general surroundings of the station (WMO, 2003). In order to simulate representative evapotranspiration rates, the soil and plant cover of the lysimeter should correspond to the soil and vegetation of the surrounding area, and disturbances caused by the existence of the instrument should be minimized. The most important requirements for the exposure of lysimeters are given below.

In order to maintain the same hydromechanical properties of the soil, it is recommended that the lysimeter be placed into the container as an undisturbed block (monolith). In the case of light, rather homogenous soils and a large container, it is sufficient to fill the container layer by layer in the same sequence and with the same density as in the natural profile.

In order to simulate the natural drainage process in the container, restricted drainage at the bottom must be prevented. Depending on the soil texture, it may be necessary to maintain the suction at the bottom artificially by means of a vacuum supply.

Apart from microlysimeters for soil evaporation, a lysimeter should be sufficiently large and deep, and its rim as low as practicable, to make it possible to have a representative, free-growing vegetation cover, without restriction to plant development.

In general, the siting of lysimeters is subject to fetch requirements, such as that of evaporation pans, namely, the plot should be located beyond the zone of influence of buildings, even single trees, meteorological instruments, and so on. In order to minimize the effects of advection, lysimeter plots should be located at a sufficient distance from the upwind edge of the surrounding area, that is, not less than 100 to 150 m. The prevention of advection effects is of special importance for measurements taken at irrigated land surfaces.

10.4.3 Sources of error in lysimeter measurements

Lysimeter measurements are subject to several sources of error caused by the disturbance of the natural conditions by the instrument itself. Some of the major effects are as follows:

(a) Restricted growth of the rooting system;
(b) Change of eddy diffusion by discontinuity between the canopy inside the lysimeter and in the surrounding area. Any discontinuity may be caused by the annulus formed by the containing and retaining walls and by discrepancies in the canopy itself;
(c) Insufficient thermal equivalence of the lysimeter to the surrounding area caused by:
    (i) Thermal isolation from the subsoil;
    (ii) Thermal effects of the air rising or descending between the container and the retaining walls;
    (iii) Alteration of the thermal properties of the soil through alteration of its texture and its moisture conditions;
(d) Insufficient equivalence of the water budget to that of the surrounding area caused by:
    (i) Disturbance of soil structure;
    (ii) Restricted drainage;
    (iii) Vertical seepage at walls;
    (iv) Prevention of surface runoff and lateral movement of soil water.

Some suitable arrangements exist to minimize lysimeter measurement errors, for example, regulation of the temperature below the container, reduction of vertical seepage at the walls by flange rings, and so forth. In addition to the careful design of the lysimeter equipment, sufficient representativeness of the plant community and the soil type of the area under study is of great importance. Moreover, the siting of the lysimeter plot must be fully representative of the natural field conditions.

10.4.4 Lysimeters maintenance

Several arrangements are necessary to maintain the representativeness of the plant cover inside the lysimeter. All agricultural and other operations (sowing, fertilizing, mowing, and the like) in the container and surrounding area should be carried out in the same way and at the same time. In order to avoid errors due to rainfall catch, the plants near and inside the container should be kept vertical, and broken leaves and stems should not extend over the surface of the lysimeter.

The maintenance of the technical devices is peculiar to each type of instrument and cannot be described here.

It is advisable to test the evapotranspirometer for leaks at least once a year by covering its surface to prevent evapotranspiration and by observing whether, over a period of days, the volume of drainage equals the amount of water added to its surface.

10.5 ESTIMATION OF EVAPORATION FROM NATURAL SURFACES

Consideration of the factors which affect evaporation, as outlined in section 10.1.3, indicates that the rate of evaporation from a natural surface will necessarily differ from that of an evaporimeter exposed to the same atmospheric conditions, because the physical characteristics of the two evaporating surfaces are not identical.

In practice, evaporation or evapotranspiration rates from natural surfaces are of interest, for example, reservoir or lake evaporation, crop evaporation, as well as areal amounts from extended land surfaces such as catchment areas.

In particular, accurate areal estimates of evapotranspiration from regions with varied surface characteristics and land-use patterns are very difficult to obtain (WMO, 1966; 1997).

Suitable methods for the estimation of lake or reservoir evaporation are the water budget, energy budget and aerodynamic approaches, the combination method of aerodynamic and energy-balance equations, and the use of a complementarity relationship between actual and potential evaporation. Furthermore, pan evaporation techniques exist which use pan evaporation for the establishment of a lake-to-pan relation. Such relations are specific to each pan type and mode of exposure. They also depend on the climatic conditions (see WMO, 1985; 1994 (Chapter 37)).

The water non-limiting point or areal values of evapotranspiration from vegetation-covered land surfaces may be obtained by determining such potential (or reference crop) evapotranspiration with the same methods as those indicated above for lake applications, but adapted to vegetative conditions. Some methods use additional growth stage-dependent coefficients for each type of vegetation, such as crops, and/or an integrated crop stomatal resistance value for the vegetation as a whole.

The Royal Netherlands Meteorological Institute employs the following procedure established by G.F. Makkink (Hooghart, 1971) for calculating the daily (24 h) reference vegetation evaporation from the averaged daily air temperature and the daily amount of global radiation as follows:

Saturation vapour pressure at air temperature T:

$$e_s(T) = 6.107 \cdot 10^{7.5 \cdot \frac{T}{237.3+T}} \qquad \text{hPa}$$

Slope of the curve of saturation water vapour pressure versus temperature at T:

$$\Delta(T) = \frac{7.5 \cdot 237.3}{(237.3+T)^2} \cdot \ln(10) \cdot e_s(T) \qquad \text{hPa/°C}$$

Psychrometric constant:

$$\Delta(T) = 0.646 + 0.0006T \qquad \text{hPa/°C}$$

Specific heat of evaporation of water:

$$\lambda(T) = 1\,000 \cdot (2\,501 - 2.38 \cdot T) \qquad \text{J/kg}$$

Density of water:

$$\rho = 1\,000 \qquad \text{kg/m}^3$$

Global radiation (24 h amount):

$$Q \qquad \text{J/m}^2$$

Air temperature (24 h average):

$$T \qquad \text{°C}$$

Daily reference vegetation evaporation:

$$E_r = \frac{1\,000 \cdot 0.65 \cdot \delta(T)}{\{\delta(T) + \gamma(T)\} \cdot \rho \cdot \lambda(T)} \cdot Q \qquad \text{mm}$$

Note: The constant 1 000 is for conversion from metres to millimetres; the constant 0.65 is a typical empirical constant.

By relating the measured rate of actual evapotranspiration to estimates of the water non-limiting potential evapotranspiration and subsequently relating this normalized value to the soil water content, soil water deficits, or the water potential in the root zone, it is possible to devise coefficients with which the actual evapotranspiration rate can be calculated for a given soil water status.

Point values of actual evapotranspiration from land surfaces can be estimated more directly from observations of the changes in soil water content measured by sampling soil moisture on a regular basis. Evapotranspiration can be measured even more accurately using a weighing lysimeter. Further methods make use of turbulence measurements (for example, eddy-correlation method) and profile measurements (for example, in boundary-layer data methods and, at two heights, in the Bowen-ratio energy-balance method). They are much more expensive and require special instruments and sensors for humidity, wind speed and temperature. Such estimates, valid for the type of soil and canopy under study, may be used as reliable independent reference values in the development of empirical relations for evapotranspiration modelling.

The difficulty in determining basin evapotranspiration arises from the discontinuities in surface characteristics which cause variable evapotranspiration rates within the area under consideration. When considering short-term values, it is necessary to estimate evapotranspiration by using empirical relationships. Over a long period (in order to minimize storage effects) the water-budget approach can be used to estimate basin evapotranspiration (see WMO, 1971). One approach, suitable for estimates from extended areas, refers to the atmospheric water balance and derives areal evapotranspiration from radiosonde data. WMO (1994, Chapter 38) describes the above-mentioned methods, their advantages and their application limits.

The measurement of evaporation from a snow surface is difficult and probably no more accurate than the computation of evaporation from water.

Evaporimeters made of polyethylene or colourless plastic are used in many countries for the measurement of evaporation from snow-pack surfaces; observations are made only when there is no snowfall.

Estimates of evaporation from snow cover can be made from observations of air humidity and wind speed at one or two levels above the snow surface and at the snow-pack surface, using the turbulent diffusion equation. The estimates are most reliable when evaporation values are computed for periods of five days or more.

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