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MEASURING EVAPOTRANSPIRATION; A REVIEW

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Abstract: Recent work has improved the possibility of calculating the evaporative water loss from a natural, vegetated surface, and the most significant contributions are reviewed in the present paper. Potential evapotranspiration is defined and the validity of this concept is carefully examined. The paper then discusses the principal approaches to the measurement of potential evapotranspiration, i.e. the transformation of measurements made from non-vegetated surfaces, the direct measurement of water losses from moist vegetated surfaces, and more or less empirical formulae, and to the measurement of actual evapotranspiration, i.e. theoretical modelling of the evapotranspiration process, physical modelling of the evapotranspiration system and the measurement of moisture flux above the evaporating surface.

Introduction

The measurement of evapotranspiration has attracted the attention of scientists of many disciplines since classical times although it is only during the past century that the problem has received anything like regular attention. Amongst early views pessimism was clearly apparent. Thus, Symons[1]) complained that "...evaporation is the most desperate branch of the desperate science of meteorology" and Penman[2]) quoted Maluschitski[3]) as stating definitively that "... no correlation can be established between the evaporation from a water surface and that for a cultivated soil, and still less in the case of a soil covered with plants". One further indication of the attitude towards the estimation and measurement of water losses was given by Abbe[4]) who admitted "... the need to know the loss of water by evaporation..." but who went on to suggest that "... in nature this is so mixed up with seepage, leakage and consumption by... plants that our meteorological data are of comparatively little importance".

Today it is clear that not only are geographers, hydrologists, botanists, ecologists, soil physicists and meteorologists etc. actively involved in this field but also that the contribution of each is playing an important role in improving our understanding of this vexing problem. No longer, it is realised, will the final solution to the accurate measurement of evapotranspiration come through an entirely physical or an entirely botanical approach, nor even through a combination of these two, since, as Crowe[5]) pointed out

"... the elements of convective and advective heat loss are as much geographical as physical problems", but rather through a multi-disciplinary approach whereby it is recognised that, in this field, no one discipline, whether physics or engineering or any other, possesses an inherent hydrological superiority.

An excellent illustration of these different but complementary interests was provided by Hastings[6]) in an unpublished paper quoted at length by Sellers[7]):

> "The possibility of estimating evapotranspiration from climatological data must interest any scientist whose work directly or indirectly involves the soil. Of these individuals the ecologist is apt to believe least that it can be done. His work has acquainted him with so many variables which influence evapotranspiration, he sees daily the effect of so many distinct microenvironments within the soil, that he may display skepticism even toward the notion that general parameters may be used to make remote approximations.
>
> At the other end of the scale the climatologist is apt to view the notion with delight because it affords him the opportunity of working with a relatively simple situation where the number of important variables is few, and they can be reasonably approximated with some degree of regularity.
>
> In between these two extremes lie the soil scientist, the hydrologist, and the geologist named respectively in the order of their decreasing skepticism and the increasing degree to which their disciplines require the simplifying, generalising and systematising of large masses of data."

During recent years there have been numerous publications of experimental evidence concerning comparative assessments of measured and calculated evapotranspiration. This literature will not be reviewed or listed in detail in this paper, since both tasks have been performed elsewhere (cf. Linacre[8]), USGS[9]). A few general observations must suffice. Apart from some excellent theoretical discussions by, for example, Rijtema[10–12]), and Chang[13]), much of this comparative work is unsatisfactory because it has been based on too short a run of data. The use of a 26-year period of observations by Smith[14]) was exceptional in this respect. In addition the discrepancies between the results of different methods is often large in relation to the magnitude of other components of the hydrological balance, such as precipitation and streamflow, and frequently falls clearly outside an acceptable margin of experimental error. Finally, although such discrepancies indicate that some, if not all of the methods are in error, there is no absolute standard against which results from given formulae or instruments may be assessed.

Largely because of such uncertainty, engineers concerned with applying evapotranspiration data to specific projects, e.g. water resources development, have often simply adopted fixed deductions for annual or seasonal evapotranspiration irrespective of short-term changes in local hydrological and climatological conditions, although this situation has been greatly changed by recent legislation in Britain, and particularly by the requirements of the Water Resources Act, 1963. Thus a purely academic interest has now been joined by a largely practical one and both have been given considerable impetus by the progress of the International Hydrological Decade.

Until quite recently it was not possible to give more than a qualified and restricted negative reply to the question: Can we calculate the evaporative water loss from a natural, vegetation-covered, land surface? However, as a result of much good work during the late 1960's by a comparatively small number of workers, including P. E. Rijtema, R. O. Slatyer and C. H. M. van Bavel in The Netherlands, Australia and the U.S.A. respectively, the situation has changed markedly. This seems an appropriate point, therefore, to take stock of past progress and to look forward to likely future developments.

Potential and actual evapotranspiration

At this stage it may be helpful to differentiate potential and actual evapotranspiration and especially to clarify the meaning of the former. The classic definition of potential evapotranspiration was provided by Penman et al.[15]) who considered it as "... evaporation from an extended surface of short green crop, actively growing, completely shading the ground, of uniform height and not short of water". Undoubtedly some of the work which has been done with a view to discrediting the notion of potential evapotranspiration and its usefulness has not fulfilled all these conditions and may therefore, be invalid although, evidently, the imprecision of the definition itself is a major obstacle.

If it is assumed that advective effects are excluded from consideration by the term "extended", i.e. of sufficient extent to minimise advectional influences, that the effects of vegetation height are excluded from consideration by the term "short", the effects of shape and roughness by "uniform" and the role of soil moisture movement by the term "never short of water", then clearly, according to this definition, PE is a climatic parameter which will not be affected by the movement of water through the soil and which will be affected by plant behaviour and plant type only insofar as these affect colour (and therefore albedo) and stomatal closure.

Equally clearly a concept so restrictingly defined is likely to be of only limited practical significance. Thus provided that all the restrictive conditions are fulfilled, the Penman concept suggests that PE represents the maximum possible evaporative loss from a vegetation-covered surface. However, these conditions are likely to be fulfilled, if at all, only for a very large surface of close-mown lawn grass in a humid environment. In all other conditions theoretical argument and experimental evidence indicate that the shape and height of the crop and the supply of large scale advective energy affects the transpiration rate in such a way that in humid conditions, say in England or The Netherlands, the actual rate of evapotranspiration under conditions of optimum water supply can exceed PE by a factor of between 1.0 and 1.4[16]. In arid conditions large scale advection must occur for if PE requires, by definition, an upwind moist evaporating surface so large that advection is obviated then the climate is no longer arid[13]. Rijtema[16] has in fact shown that in arid climatological conditions maximum evapotranspiration may exceed PE by a factor as high as 1.9. In a series of related papers Morton[17-19] clearly recognized the important role played by advection in the potential evapotranspiration process although his empirical approach to the relationship between potential and actual evapotranspiration can hardly be hailed as a step forward.

The effect of aerodynamic roughness on the turbulent transfer of moisture and energy from the vegetation surface is an important factor in evapotranspiration, as was emphasized by van Bavel[20]. This is true even if the conditions of complete canopy cover and uniform height are maintained for, in general, evapotranspiration increases with vegetation height due to increased roughness and zero plane displacement at a given windspeed[13]. The coefficient of turbulent exchange, in fact, increases by a factor of 2 with a change in vegetation height from 10 cm to 90 cm and by a factor of more than 5 with a change from a short cut green surface at about 2 or 3 cm (as implied in the classic Penman definition of PE) to a vegetation height of 90 cm[21]. This large variation in the turbulent exchange coefficient is quite sufficient to explain why PE as defined by Penman is frequently exceeded by the evapotranspiration rate from, say, typical agricultural crops[22]. Relations between aerodynamic characteristics and PE for some types of tropical rainforest have recently been discussed by Brunig[23].

A further limitation of the Penman-type PE is that the stipulation "not short of water" involves a rather arbitrary concept, which refers largely to soil moisture status and which holds good only under conditions of low evapotranspiration. In high evapotranspiration conditions internal plant stresses can develop such that, even with an optimum soil moisture status, the stomata may close, thereby reducing the transpiration rate[22]. Thus a number of authorities have reported day-time stomatal closing in wet tropical rainforest, under the influence of a high heat load, whilst data for irrigated spring wheat and potatoes were reported by Rijtema[22] and Endrödi and Rijtema[24] respectively. However, not *all* plants react in this way and thus it seems clear that the type of distinction made by Chang[13] between conventional and non-conventional plants might be helpful. Certainly in classic experiments van Bavel et al.[25] and Fritschen and van Bavel[26] found that unsurpassed daily rates of evapotranspiration were maintained from a patch of sudangrass with no visible evidence of moisture stress and no midday-depression of transpiration which would have been convincing evidence of stomatal influence.

Plant physiological – and particularly stomatal – 'control' of evapotranspiration is a complex problem and dangerous ground for the non-specialist. The problem has been the subject of a large number of investigations, the more important of which were reviewed by Lee[27] with subsequent discussion by Idso[28], van Bavel[29] and Szeicz[30] and Lee[31]. Basically, there are two main schools of thought. First, it has been argued that with conventional plants in conditions of optimum water supply, stomatal closure exerts a significant influence on evapotranspiration only when the stomata are almost closed. Also, since stomatal aperture is determined by the difference in turgor pressure between guard cells and subsidiary cells and since turgor pressure may be influenced directly by the general levels of plant turgor and indirectly by such factors as light, temperature, atmospheric humidity, carbon dioxide and wind[32], then by maintaining optimum moisture conditions (a stated condition for PE) one removes a major source of variation and leaves a situation where the diurnal variation of stomatal aperture (as governed, say, by daylight and temperature) will closely coincide with diurnal variation in the availability of energy for the conversion of liquid water within the leaf to water vapour. A second view is that in many plants, even under optimum moisture conditions, the stomata may regulate rates of transpiration, i.e. that vegetation covers are not passive, evaporating 'wicks'. This viewpoint, at first argued theoretically, has been increasingly substantiated by experimental evidence, including, in more recent years, experiments aimed at reducing transpiration losses by artificially reducing stomatal aperture (cf. Davenport et al.[33]).

Such problems as have been discussed in the foregoing paragraphs have long been recognised by workers in this field. Small departures from the ideal situation defined by Penman et al.[15] may result in large differences in PE estimates and for this reason the concept of PE has been redefined, and renamed, on a number of occasions. Thus a more realistic definition of the maximum evaporative loss from a vegetation-covered surface was proposed by van Wijk and de Vries[34] in terms of wet surface evaporation, defined as the maximum evaporation rate from a wet surface of similar shape, colour and dimensions as the crop under consideration. The evaporation rate so defined is a more useful concept since it gives the maximum value under any climatological conditions[22]). Pruitt[35]) developed the notion of potential maximum evapotranspiration to allow for the (normal) situation in which advected energy is an important factor in determining evapotranspiration rates. Finally, van Bavel[20]) in a major contribution to the study of potential evapotranspiration, noted that PE can be defined for any vegetation cover in terms of the appropriate meteorological variables and the radiational and aerodynamic properties of that cover, suggesting that: "When the surface is wet and imposes no restriction upon the flow of water vapor, the potential value is reached".

In whichever way potential evapotranspiration is defined, there are certain elements of the basic Penman philosophy which remain applicable. It seems appropriate, therefore, to conclude this part of the discussion by contraposing two quotations which largely summarise the main arguments:

> "I have never seen from any biological source that evaporation or transpiration through the plant is a vital process in the sense that the plant itself does something about it. The amount of energy that a plant can produce, even if burned all up, is insufficient to keep its normal daily transpiration going for more than about 2 days. There is not in the plant a source of energy for transpiration anyway. I firmly believe, and I am going on with my job on the assumption, that the water use by plants is not a vital process. If I fail to interpret it in physical terms, it is not because there is no physical explanation, but simply because I am not sufficiently competent to do the job" (H. L. Penman in discussion of Wicht[36]).
>
> "If plants are indeed 'wicks', the plant scientist must argue that they are wicks of a unique kind. They are wicks with varying hydraulic conductivities. They are wicks coated with an epidermis that changes its permeability to gaseous exchange diurnally and seasonally and shows characteristic variations with plant species and type...
> The interactions between plants and their environment with respect to water loss present one of the most interesting problems of the Hydrologic Decade. We can do justice to the problem by accepting the active roles of both plants and environment" (R. Lee[31]).

Having now discussed the concept of potential evapotranspiration it remains to consider briefly whether that concept has validity or at least sufficient validity to make its measurement worthwhile. A few selected examples will suffice to confirm that this is the case. There are, for example, the climatological applications of PE in water balance studies of the type developed by Thornthwaite and his colleagues in the U.S.A. (Thornthwaite and Mather[37]); Carter[38,39]); Van Hylckama[40,41]) and Green[42]) and Howe[43]) in Britain. In this context, maps of water balance parameters such as water surplus and water deficiency have proved particularly useful in quantifying regional differences in water resources[44]).

Also, from the purely hydrological standpoint, there are many types of area in which water losses almost certainly occur at the potential rate for much of the time. Obvious examples are irrigated areas and upland areas in Britain where the precipitation is both heavy and frequent, as well as areas with shallow groundwater bodies such as The Netherlands, river bottomlands and areas of phreatophytic vegetation in semi-arid environments. Thus, it has been estimated that the Nile is depleted by about 40% of its volume during its passage through the Sudd marshes[45]) and that the total losses of water from phreatophytic vegetation in 17 western states of the U.S.A. amounts to between 20 and 25 million acre-feet per year[46]).

Measurement of potential evapotranspiration

Three main approaches to the measurement of PE have been evolved. These are a) the transformation of measurements made from non-vegetated surfaces, b) the direct measurement of water losses from moist vegetated surfaces, and c) more or less empirical formulae.

a) The first approach relies mainly on the use of evaporimeters and evaporation pans. Evaporimeters range widely in design from the earlier versions suggested by Piche in 1872 and Bellani to their modern derivatives[47]) and new designs are still being hopefully suggested (cf. Martinez[48], Wilcox[49])). At best these instruments provide a measure of the drying power of the air although it is doubtful if they do even that consistently and accurately. Very rarely are they able to provide a value which closely approximates potential water loss.

Evaporation pans also come in a wide variety of shapes and forms, with the newer designs concentrating on small diameter, heavily insulted fibreglass pans in which a reasonably close control of the heat budget of the pan is possible. In terms of widespread use, however, and certainly of the widespread availability of data, the two main types are the U.S. Weather Bureau Class A pan and the British Meteorological Office sunken pan. A recent review by Holland[50]) of evaporation measurements in the British Isles drew attention to the fact that in some circumstances the British pan gives results which may approximate PE (i.e. a pan coefficient of unity). Although one would not expect a water surface to behave like a normal vegetated one, it is of interest to note that under normal climatological conditions in The Netherlands maximum evapotranspiration from a grass cover of 10–15 cm height closely approximates the evaporation rate from sunken pans. In addition, Rijtema[16]) discussed other Dutch data which indicated a close agreement between measured water loss from sunken pans and the E_0 values calculated with the Penman equation. Chang[13]) reviewed evaporation pan and other measured data and concluded that "... the evaporation pan is as accurate as any formula or field instrument for estimating potential evapotranspiration in a humid climate and when properly exposed, the potential maximum evapotranspiration in an arid climate".

b) The second approach involves the use of irrigated evapotranspirometers in which the soil moisture content is maintained at a level which permits water losses to occur at the potential rate and for which, therefore, a simple balancing of precipitation and irrigation inputs against drainage output suffices to permit the calculation of PE. Aspects of operating this type of equipment have previously been quite fully discussed[51,52]) and the only point which needs re-emphasis at this stage is that provided the correct operating conditions are adequately maintained evapotranspirometers should provide an adequate measure of potential water loss. Where a choice must be made between the two, they would certainly be preferable to an evaporation pan.

c) Of the many formulae which have been developed to estimate potential evapotranspiration, those of Penman and Thornthwaite have emerged as the most generally applicable. Again, both have been fully discussed on numerous occasions and we need note only that both were largely empirical, particularly as originally stated, and that this has resulted in many attempts to refine and improve them both by their original authors and by subsequent workers.

One frequently proposed improvement to the Penman method involves the insertion of measured net radiation values in place of the original radiation terms. It should be pointed out, however, that this will result in an improved estimate of PE only if the network of radiation instruments is sufficiently dense to enable a representative sampling of vegetation type having different albedo and surface temperatures. Otherwise the gain in accuracy of the point measurement tends to be lost in the extrapolation to an areal estimate. This problem was highlighted by Hershfield[53]) who pointed out that "Since the whole heat and water transfer process is a microrandom affair, sampling at any point will produce variations in time. Good estimates of these variations in time about their means and the variations among points are essential". For many purposes, therefore, a more practical approach is to measure the global radiation and then to use the proper albedo of the different vegetation covers, using an empirical relation, such as the one proposed by Penman, to calculate the net longwave radiation. The main advantage of this procedure is that the measured global radiation data hold good for large areas.

Further improvements aimed at reducing the empirical element in the Penman formula have been proposed from time to time[54, 55, 20]. One of the most effective modifications was that by van Bavel[20] who used a combination of a surface energy balance equation and an approximate expression of water vapour and sensible heat transfer to formulate an equation relating potential evaporation to net radiation, ambient air properties and surface roughness. This equation, from which all empiricism is excluded, gave excellent agreement for 24-hour totals and acceptable agreement for hourly values when measured and calculated evaporation from open water, wet soil and well watered alfalfa were compared.

The increasing use of electronic computers to solve the Penman equation has resulted in a proliferation of computer programmes and translations. One therefore welcomes the recent description by Chidley and Pike[56] of a generalised programme that has a wide application with regard to location and variety of input data.

Thornthwaite's temperature-based formula for potential evapotranspiration has been discussed in detail on a number of occasions (e.g.[57–59]). In those conditions in which air temperature and net radiation availability are close related, the formula works quite effectively; in other conditions it is more or less unsatisfactory but continues to be widely used because of its minimal input data requirements.

Measurement of actual evapotranspiration

Once one turns attention from naturally wet, or irrigated areas however, one is obliged to consider the problem of *actual* evapotranspiration and in particular the great difficulties of measuring this phenomenon. Having removed the constriction of adequate water supply which is conveniently imposed by the concept of PE, it is necessary to make allowance in the calculations for all factors relating to the soil and plant cover, some of which it has hitherto been convenient to ignore or to lightly dismiss. In effect, it is now necessary to look at the evapotranspiration process not simply as a moisture and energy exchange taking place at a single, albeit somewhat complicated, interface, i.e. that between the atmosphere and the soil-vegetation cover, but as a flow phenomenon, which starts in the soil beyond the immediate reach of the plant root system and which involves movement within the soil pores and interstices to the roots, and then transport through the conducting vessels of the plant itself to the plant/atmosphere interface. Thus, all the factors which affect the capillary movement of moisture in the soil are now relevant, as also are the resistances imposed on the passage of water by various parts of the plant system in all climatological and hydrological situations.

Clearly, therefore, any consideration of actual evapotranspiration must recognise that every moment of every day brings a unique set of conditions to every square centimeter of the ground surface and, that being so, it would seem equally clear that no formula or equation which relies solely on meteorological or climatological observations can be expected (except fortuitously) even to approximate the rate of evapotranspiration. Furthermore, one might reasonably suggest that it is pointless to spend time in considering such an approach since one could obtain as reasonable results by simply calculating PE from one of the more reliable formulae and then reducing the values obtained in proportion to the degree of soil moisture depletion. This was the approach proposed by Penman[60]) and subsequently adopted by the UK Meteorological Office in their mapping of soil moisture deficit and actual evaporation[61]).

Where, however, the demand is for a value of accumulated actual water loss over long periods of time e.g. one year, it has been found that formulae such as those of Turc[62]) and Budyko[63]) give comparatively satisfactory results, especially with the substitution of Penman's E_0 or Kohler's E_L for the rather clumsy terms of the original authors[64]). Lewis[64]) (Table 4, p. 71) presented data showing good annual correlations using the Turc and Budyko formulae, although mean values over a period of four years were even better e.g. for watershed A, 20.4 inches, 20.4 inches and 20.1 inches for measured rainfall minus runoff, the Turc formula and the Budyko formula respectively and for watershed B, for the same three categories, values of 14.9, 14.5 and 14.1 inches. Not surprisingly, therefore, was Lewis able to conclude: "The equations of Turc and Budyko relate the evapotranspiration potential of the environment to the variable moisture supply to give close estimations of measured consumptive use" (i.e. actual water use).

Turning attention once more to shorter term estimates, however, the situation is far more complex. Basically, there would appear to be three main approaches, i.e. 1) Theoretical modelling of the entire evapotranspiration process from soil to atmosphere using combination energy-balance and vapour transport formulae and taking into account surface- and other resistances of the evaporating vegetation surface. This approach has been successfully developed by a number of workers including Monteith[65]), Rijtema[16]) and Szeicz et al.[66]).

2) Physical modelling of the evapotranspiration system in the sense of

water balance calculations for known areas or volumes of vegetation or vegetation-covered ground surface in which evaporative loss is derived as the residual item in the water balance equation (Inflow = Outflow + or − Δ Storage).

3) Measurement of the flux of moisture above the evaporating vegetation surface, since the total amount of actual evapotranspiration must pass into the overlying air layers where it will be reflected in humidity and temperature gradients. Each of these three approaches will now be briefly discussed.

Combination formulae

It became clear soon after its introduction and subsequent minor modifications that the Penman formula was not only a successful means of estimating potential evapotranspiration but also an excellent and readily adaptable model of the evapotranspiration process. Provided that the appropriate crop and soil factors could be incorporated it held out considerable promise for the successful estimation of actual evapotranspiration. A number of workers in different countries have made important contributions in this field. In Britain the work of H. L. Penman himself and of J. L. Monteith and his collaborators, particularly G. Szeicz over the past decade or so, comes immediately to mind, whilst over the same time period in The Netherlands, P. E. Rijtema's work along similar lines has been rigorous and successful.

In both cases investigation proceeded from the premise that whereas in the Penman combination formula the simplifying assumption of a wet vegetation surface was used, in fact when, as is normally the case, the vegetation surface is not wet the rate of evaporation must be reduced because of the diffusion resistances imposed by the soil pores and stomata. At an early stage Penman and Schofield[67]) formulated the combination method to include the stomatal resistance of the vegetation cover. Subsequently a solution to the difficulty of estimating stomatal and other surface resistances was suggested by Monteith and Sceicz [68]) who showed that the effective surface resistance of field crops could be estimated from their radiative temperature and by Monteith[69]) who showed that this resistance could also be calculated from temperature, vapour pressure and wind profiles over the vegetation surface. Later, Monteith[65]) presented a generalised version of the Penman formula incorporating the stomatal resistance factor and in subsequent work Szeicz et al.[66]) and Szeicz and Long[70]) showed that the mean aerodynamic resistance can be calculated from windspeed and surface roughness by reference to crop height. Calculated rates of actual evaporation for water, pine forest, and for two agricultural crops agreed well with measured rates of transpiration in both southern England and California.

Studies of Rijtema[16,21,22] and of Endrödi and Rijtema[24] presented a quantitative description and physical formulation of the entire evapotranspiration process from the soil to the atmosphere, including, in addition to meteorological conditions, such soil physical properties as soil moisture suction and capillary conductivity and vegetational properties such as rooting characteristics, internal resistance to liquid flow from root surface to sub-stomatal cavities, suction in the leaf tissue in relation to stomatal reaction, ground coverage and vegetation height. Rijtema showed that by taking all these factors into account, actual evapotranspiration for weekly periods could be calculated using a combined aerodynamic and energy balance approach. Comparisons of fortnightly data on calculated and measured evapotranspiration from both irrigated and non-irrigated summer wheat showed "reasonable agreement"[22].

Some workers have argued against the type of canopy resistance model proposed by Penman and Schofield and elaborated by Monteith or Rijtema, on the grounds that treating the canopy as though it behaves as a large leaf may be interesting but cannot be correct[71]. Thus Tanner and Fuchs[71] suggested that the normal diffusion resistance model is not applicable either to vegetation canopies or to soil and instead developed a combination formula, relating evaporation from a drying soil to the PE, which uses surface temperature as the only additional measurement to the standard PE combination formula.

For most general purposes and for large scale, e.g. catchment, application, important considerations during this period of continuing development and refinement of the combination formulae will continue to be ease of application and ready availability of the basic input data.

Water balance approach

This has been applied at a number of different scales including lysimeters, water table fluctuations, river basins and small experimental watersheds, and moisture fluctuations within the soil profile.

a) Numerous lysimeter studies have been reported in the literature, the aims in each case normally being to reproduce the soil profile within a water-tight container, to induce a typical vegetation cover with a representative root system to develop, and to expose this sample surface to the same meteorological or climatological conditions as those experienced by the area being sampled. Then evapotranspiration equals precipitation minus percolation through the lysimeter, the accuracy of the allowance needed to account for variations in soil moisture storage varying with the length of period of measurement. There are many experimental difficulties associated with the use of lysimeters. One of the more important would seem to be that it is virtually impossible to reproduce the soil profile accurately so that, in turn, vegetation development may not be typical. Again, in most cases the shallow depth of these instruments prevents both deep percolation and the capillary rise of moisture from some depth within the soil profile, unless a water table is maintained artificially, in which case the lysimeter may be representative only of rather special shallow water table conditions. In this connection the lysimeters developed by Feddes[72]) are of particular interest. The water table depth in these is controlled by the surrounding field water table level so that water management within the lysimeter closely approximates that in the area represented by it. Another difficulty is that representative meteorological and climatological conditions will not be encountered unless the lysimeter and the surrounding area form a uniform and homogeneous surface. Finally, however carefully the above problems are countered, it remains inevitable that an extensive area of artificial boundary conditions (the lysimeters walls and bottom) have been imposed on a comparatively small volume of soil. This last difficulty is not helped by the fact that size is largely determined by cost of installation (or vice-versa) and also by the need to weigh the entire instrument if changes of moisture content are to be determined accurately.

Weighing may be carried out either mechanically, or mechanically and electrically in which case the dead load is counterbalanced and changes in the live load (e.g. moisture content changes) are recorded through a strain-gauge cell. Alternatively, floating lysimeters may be used, whereby weight changes are computed from the changes in fluid level around the soil tank, or hydraulically when the weight is supported on a water-filled container connected to a manometer or pressure gauge. Recent developments in the use of neutron probes for measuring lysimeter moisture changes (c.f.[73]) may go far towards overcoming the normal size restriction.

Since size of the lysimeter surface also restricts crop type, it is found that most lysimeter studies have been carried out with comparatively small crops e.g. grass. Indeed, there are only isolated examples of really large lysimeters which are able to support trees, amongst which those at Castricum in Holland are probably best known[74]). These lysimeters are 25 metres square and 2.5 metres deep and are obviously too large for moisture changes to be determined by any of the weighing techniques outlined above. Instead, soil moisture contents are determined from periodic sampling.

b) The calculation of evapotranspiration from water table fluctuations represents one of the oldest approaches to this problem and was well exemplified in the classic paper by White[75]) by Troxell's work on the floodplain of the Santa Anna river[76]) and more recently by Meyboom[77]) in the Canadian prairies. The main disadvantages of the method are the large number of influencing variables (apart from evapotranspiration), many of which e.g. groundwater flow into and out of the area, are difficult to determine with a high degree of accuracy, and the fact that the method can be used only where the water table is at a shallow depth below the ground surface.

c) An approximate measure of long-term evapotranspiration may be determined by considering the major water balance components of a river basin. Assuming that over a period of one year subsurface storage changes are negligible, a simplified water balance equation may be written: evapotranspiration = precipitation minus runoff. For any but very small basins, however, there are difficulties in obtaining reliable values of precipitation from existing gauge networks and also storage/lag problems at each year end when late precipitation may not appear as runoff until the early months of the following year.

d) Some of the problems inherent in river basin determinations of actual evapotranspiration are avoided in small experimental watersheds in which detailed measurements are made of a wide range of parameters. In this case the main thesis is that if the water balance equation $P-Q-E-\Delta S-\Delta G=0$ (where P is precipitation, Q is streamflow, E is actual evapotranspiration and ΔS and ΔG are changes in soil moisture and groundwater storage respectively) can be solved, then it is likely that the measurements or estimations of the individual components of that balance are satisfactory.

Evidently, this may be an erroneous supposition if discrepancies in the assessment of individual parameters are fortuitously complementary, although this source of error can usually be guarded against by making specimen water balance calculations for different time periods within the same run of data. Since precipitation, streamflow, soil moisture and groundwater measurements can almost certainly be made with a greater accuracy than the corresponding measurements or estimations of evaporative losses, it can be argued that the value of E which consistently gives the best result in the water balance equation is the most "suitable". Work of this type has recently been presented by Dunin[78] and by Pegg[79].

e) A further check on the small watershed water balance can be provided by calculating the partial water balance for the soil profile only. The important work done by Thornthwaite and his colleagues on the climatic water balance (cf.[37]) has substantiated the close relationships and inter-relationships between P, E and ΔS. In the final analysis an approach through soil moisture measurement and particularly the determination of successive soil moisture profiles, may well hold out most hope for accurate determination of actual evapotranspiration since it is only within the soil profile that one can obtain a direct measure of the amount of water withdrawn by vegetation cover. The principal disadvantage of this approach is the need for considerable replication of moisture measurements, although this problem is eased by using a neutron probe[80]), and by the careful choice of measuring sites where dominantly lateral (as opposed to vertical) movements of moisture within the profile are not present. In many forested areas where lysimeter studies are not practicable, neutron soil moisture measurements may represent the only realistic approach to the measurement of evapotranspiration[81]).

An extension of the soil profile water balance approach concerns the determination of salt movement within the soil profile and its use as an index of evapotranspiration. Chloride translocation, for example, was investigated by Doering et al.[82]) and by Dylla and Stuart[83]) who concluded that, even under the most ideal conditions, the method was not accurate.

Moisture flux measurements

Determinations of actual evapotranspiration from measurements of the flux of moisture above the evaporating surface have been investigated in a number of different situations.

a) A theoretical approach was developed in detail by Thornthwaite and Holzman[84]) and later modified by Pasquill[85,86]) and Rider[87,88]). This approach is based upon the fact that evapotranspiration into the lower layers of the atmosphere will tend to establish a moisture gradient from the evaporating surface into the overlying air, and that turbulent motion will tend to break that gradient down and so establish uniform moisture conditions above the evaporating surface. If then both the moisture gradient and the turbulent motion of the air can be accurately measured, the contribution of water vapour from the evapotranspiration process can be deduced.

Instrumental limitations and the non-generality of the formulae were at first decisive in preventing the wider development of this approach. Technological developments have reduced many of the instrumental limitations, at least in relation to research investigations, whilst the recent publication of a general solution to the mass-transfer equation by Shih and Dracup[89]) provided a new approach to the study of evaporation from natural or artificial water surfaces, although not from vegetation-covered land surfaces.

At the present time direct measurement of the moisture flux is being investigated in two main ways: namely, leaf chamber studies and the eddy correlation method.

b) In leaf chamber studies, such as those reported by Bierhuizen and Slatyer[90]) and by Jarvis and Slatyer[91]), independent, continuous and simultaneous measurements are possible of the water vapour and carbon dioxide exchanges between each surface of a leaf and the surrounding atmosphere under controlled conditions of visible and total radiation, air and leaf temperatures, and carbon dioxide and water vapour concentrations. Field measurements from an entire plant or collection of plants are possible in larger plant chambers such as that developed by F. W. Went and described by Ashby[92]) and Stark[93,94]). This is a clear plastic chamber of 6 cubic decimetres volume which may be placed over a small living plant in the field and within which changes in relative humidity are measured by a hygrosensor and registered on a sensitive galvanometer. Stark found the method accurate and was able to make more than 400 transpiration measurements every day.

Such measurements will undoubtedly help towards a better understanding of the transpiration process although in terms of a meaningful measurement of actual water loss from a natural surface those from individual leaves may be of comparatively little value. Thus, within a vegetation cover, leaves do not exist in isolation but in such large numbers that mutual interference in terms of incoming and outgoing radiation, humidity and sensible heat must occur: again, leaf and in some cases plant chamber studies are concerned primarily with the final phase of the transpiration process only, i.e. the conversion of liquid water within the plant to water vapour and its subsequent transfer into the atmosphere, thereby ignoring many of the preceding stages of moisture movement and moisture stress within, say, the soil and root systems.

c) Many of the weaknesses of the leaf and plant chamber approach are avoided when direct measurements are made of the moisture flux over an existing, natural vegetated surface as in the eddy correlation method which was pioneered in Australia by Swinbank[95]) who demonstrated that fluxes could be determined from the correlation of temperature and humidity fluctuations with the vertical component of wind velocity. In order to avoid laborious data computations it was necessary to develop an instrument in which the relevant calculations were carried out instantaneously. Having demonstrated the feasibility and validity of this concept[96]) it was then desirable to design a small, portable instrument, subsequently called the "Evapotron", which could be used in the field. Preliminary tests were carried out in 1961 and the instrument was later used in extensive investigations[97]). By means of delicate sensing devices simultaneous measurements are made of the minute eddy fluctuations of humidity, wind and temperature above the evaporating surface. This information may be fed directly into a computer and an output of net upward movement of water vapour from the evaporating surface obtained. As described by Dyer and Maher[98]) "The performance of the Evapotron is now very close to the optimum which can be achieved with the present fine-wire sensors", which meant that whilst the measurement of heat transfer was satisfactory the response time of the wet bulb was a limiting factor in evaporation measurement.

Dyer et al.[99] later described an improved instrument for measuring heat transfer called the "Fluxatron" in which slow eddies which do not contribute to the eddy flux can be filtered out, which has a much lower power consumption and which can be used in the field by relatively unskilled personnel. It was intended to extend its use to evaporation measurement when an alternative to the fine-wire sensor was found for the humidity measurement. Such an alternative, a barium fluoride film humidity sensor developed by Jones and Wexler[100] was described by Goltz et al.[101] who concluded that this sensor had sufficiently rapid response to allow reliable eddy correlation measurements of vapour flux within a metre of the surface, in comparison with the 4 metres necessary for the Evapotron and Fluxatron.

Although such instruments are still clearly in the process of development, they will undoubtedly eventually come into widespread use as a standard measuring device. Ironically, this is likely to raise almost as many problems as it solves, particularly in connection with the representativeness of the measuring sites and the degree of replication required, since the more sophisticated the measured data are, the less likely are they to be broadly representative of surrounding conditions. However, despite the instrumental and theoretical progress which has been made in the field of evapotranspiration measurement, "... little work has been done on the problem of applying the point measurement procedures to watershed size areas"[102] and this now obviously represents a major research deficiency.

Assuming that this deficiency may be rectified satisfactorily in the comparatively near future, it would seem reasonable to conclude that in little over a century we have moved from a stage of extreme pessimism to one of guarded optimism concerning the feasibility of measuring evapotranspiration with a degree of accuracy normally accepted for other major hydrological and climatological parameters. Viewed in the most generous terms, this seems but a modest achievement in a century which has seen such striking advances in other natural and environmental sciences.

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