The role of vegetation in soil water problems

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ABSTRACT: The main mechanism for producing unsaturation is evaporation from growing plants. In some clay soils the drying produces cracks whose persistence may determine soil permeability at saturation. Movement of water, and limiting values of soil water contents, are determined by soil moisture potentials, and energy supply is rarely a controlling factor. The lower limit of water content depends on the depth of root penetration, and the degree of ramification within the root depth: plant and soil characters determine these quantities. Adding the concept of « accessibility » to that of « availability » reconciles some clashes in field evidence about how long actual evaporation remains equal to potential evaporation. Examples of plant/soil interactions considered include a range of soil depths, contrasts in plant type and different climates.

RÉSUMÉ : Le mécanisme principal conduisant à la non-saturation est l'évaporation des plantes en végétation. Dans certains sols argileux, le séchage produit des fissures dont la persistance peut déterminer la perméabilité du sol à la saturation. Le mouvement de l'eau et les valeurs limitantes de la teneur en humidité du sol, sont déterminés par les potentiels de l'humidité et une fourniture d'énergie est rarement un facteur de contrôle. La limite inférieure de la teneur en humidité dépend de la profondeur de pénétration des racines, et du degré de ramification dans la zone des racines : les caractéristiques du sol et des plantes déterminent ces quantités. Si on ajoute le concept d'« accessibilité » à celui de « disponibilité » peut réconcilier certaines oppositions sur la question combien de temps l'évaporation actuelle demeure égale à l'évaporation potentielle. Des exemples d'interactions plante-sol doivent comprendre une série de profondeurs de sols, de contrastes dans le type des plantes et de climats différents.

I. INTRODUCTION

Most soils consist of mineral particles, with a size distribution that determines the texture of the soil, arranged or aggregated in a way that determines the structure of the soil. In general, soil management seeks to produce the best structure that the texture will permit. To give scale, some 40 or 50 per cent of the bulk volume of soil is non-solid pore-space that can be occupied by fluid: when all of the fluid is water the soil is saturated; when drainage is allowed or imposed some of the water is replaced by air, and the soil is then unsaturated. In fine textured soils with little structure, free drainage may remove only a small amount of water, leaving the pore-space with no detectable air content: in coarse textured soils, or those with an open structure, free drainage can remove a lot of water. Although drainage may be slow, it is often convenient to consider it as effectively complete within a few days, and to describe the state reached as "being at field capacity". The problems of water in the unsaturated zone are those of soil at field capacity and drier than field capacity, and the broad hydrological significance of the concept is that, in general, the whole of a soil profile must be brought back to field capacity before there is any drainage. Continued slow drainage may dry a soil beyond field capacity—the effect is sometimes very important— but the main mechanism for drying is evaporation, and although significant and important evaporation can take place from the surface of bare soil the most important desiccating agency is a growing crop. Liquid water is taken in at the roots, passes through the woody tissue to the leaves and vaporizes within the leaves, so that its final journey to the atmosphere is as vapour. This too is an evaporation process, long ago given the name "transpiration", and no other supplement to the vocabulary of plant water studies is needed.

It is helpful to idealise the state of the soil at field capacity by assuming that all the pore-space outside the structural aggregates is completely drained, and the aggregates themselves are saturated. Root action will then dry the aggregates in two possible ways. First, as water comes out it is replaced by air, with no change in the bulk volume of the aggregate: second, as water comes out it is not replaced by air but the particles are pulled into closer packing to leave a smaller bulk volume still saturated. Natural soils can come anywhere between these extremes, depending on the clay content and the nature of the clay. If the shrinkage is isotropic then one-third of the movement occurs in the vertical, and in southeast England lowering of the surface of clay soils by about 5 cm has been measured in occasional summers when the net extraction of water by plant roots is known to be about 15 cm as rainfall equivalent. The consequences are more important in engineering than in hydrology: there is structural damage to roads and to buildings on shallow foundations. The associated horizontal movement is much more important hydrologically because the vertical cracks it produces permit rapid acceptance of storm water, and may cause significant transfer to considerable depth in the profile before the soil above is brought back to field capacity. Other important effects, both in agriculture and hydrology, occur in long term behaviour. Whereas the shrinkage is effectively instantaneous, the swelling is so slow that it may take many months of contact with free water before the cracks close (and the surface rises to its initial level): the winter permeability of many clay soils at nominal "saturation" depends on the degree of unsaturation produced by vegetation during the summer, and in some parts of the world there is little doubt that winter recharge of aquifers overlain by clay soils would be very inefficient without it.

The phenomena of shrinkage and swelling complicate both laboratory and field experiments, and very few analysts have attempted to include them in theoretical studies of water movement in the unsaturated state. Present practice is to ignore or avoid the complications, and even then, as several papers in this symposium show, analysis is not easy and progress is slow. Basically the problem is two-fold: what is the condition for equilibrium? How does redistribution take place when equilibrium is disturbed, either by addition or extraction of water? As stated the main extractant is the growing crop, but it will be a long time before there is any comprehensive physical theory of soil water movement in response to root action, but when it does come it will include concepts applicable whether or not there are roots. Accordingly, the first part of this survey is a brief account of some of these concepts leading to a qualitative description of how the spatial and temporal distributions of roots and root activity affect the problem. The second part examines a few selected examples of how climate, soil and plant character may affect the water content of the unsaturated zone. There is now a good nucleus of reliable field evidence for testing of theoretical ideas, and the International Hydrological Decade should produce more.

II. FUNDAMENTAL IDEAS ON WATER POTENTIAL

In the study of soil water relations much use is made of the concept of "potential", sometimes precisely, sometimes more loosely but without error, and sometimes too loosely, with a risk of error or misunderstanding.

Precisely, the potential at a point is the work done in transferring unit quantity from a place of zero potential to the point: in general, the reference place is not specified, and most of the physics deals with changes of potential, usually in terms of potential gradients, and frequently through a formal equation: force, $F = -\partial v/\partial x$. In the absence of other restricting forces, this force will produce an acceleration, but in nearly all systems there are restricting forces that increase with velocity. The acceleration phase is a transient phenomenon, and when F is exactly balanced by the restricting forces a steady motion results. The equation of motion becomes:

$$\text{flux, } f_v = -k_v \partial v/\partial x, \tag{1}$$

where k is a conductivity. For water movement in saturated soil this is the familiar Darcy equation, and there have been numerous attempts to apply it to unsaturated flow: a review by Marshall (1959) will almost certainly be brought up to date by speakers in this symposium.

But at least one other way of fluid transfer is important, namely random movement in diffusion processes. Here the movement of each molecule is quite independent of that of its neighbours, and Einstein showed that the statistical average of the random motions could be described by a "diffusion" constant for the system. Out of this there emerges a theoretical justification for an empirical relation:

$$\text{flux, } f_D = -D\partial c/\partial x, \tag{2}$$

where $\partial c/\partial x$ is a concentration gradient. Because this equation looks so much like the one before, the two are often (and safely) treated as being the same: the danger arises when, as is sometimes possible, the concentration can be expressed in terms of a potential, and the equation takes the form:

$$f_D = -k_D \partial v/\partial x. \tag{3}$$

The risk lies in accepting the simple algebra of $f_v + f_D = -(k_v + k_D)\partial v/\partial x$. At equilibrium the first inference is safe, *i.e.* the condition of zero flux is zero potential gradient, but it can be quite wrong to infer that if c and v are measured at equilibrium there is necessarily a unique relationship between them. In the physics of soil water c is the water content of the soil by volume fraction, and, following Schofield (1935), the potential is the decrease in free energy below that of pure water in bulk (the reference state), frequently expressed as a logarithm for convenience in graphical representation, and the logarithm is symbolised by pF to save words. Thinking only of drying, and of the unsaturated state, the pF curve of a soil is relevant to the flow of liquid water only when the potential used is the "capillary potential" (Buckingham, 1907) or the "matrix potential" (Slatyer and Taylor, 1960), that is when the measurements have been made in a system free from salt. Addition of salt will change v without changing c, and hence use of equation 1 to describe the viscous flow of liquid water is misleading if the total potential is used for v: somewhat paradoxically use of equation 2 will be safer, treating the viscous transfer as though it were a diffusive process governed by a "diffusivity" constant, D.

A field example will support the academic argument. It is often good agricultural practice to drill fertiliser close to the seed. As the salt goes into solution the free energy of the solution becomes very much less than that of the soil water around the seed, *i.e.* $\partial v/\partial x$ between seed and fertiliser is very large, but Rose (1963*a*) has shown that there can be no significant movement of water from seed to fertiliser: there will be a small but unimportant vapour flux, governed by equation 2, where c is the concentration of water vapour in the soil air.

Interpretation of this example needs a concept not so far mentioned: the semi-permeable membrane. The surface of a solution is a perfect semi-permeable membrane: water molecules can pass freely, but solute molecules cannot pass at all. In the approach to equilibrium between a solution and the vapour over it the rate is governed by equation 2, but because there is here a unique relationship between c and v, the final equilibrium is attained when ∂v across the surface is zero. The rate may also depend on an energy supply, because it will involve either evaporation or condensation, an aspect to be considered later. At equilibrium, however, the potential is uniquely related to the relative humidity of the air over the surface, and though by no means easy, measurement of the equilibrium relative humidity is the simplest way of estimating soil moisture potential (Monteith and Owen, 1958; Richards and Ogata, 1958). The range of agricultural importance is from 100 per cent down to about 98 per cent, and it is unlikely that the important range in hydrology is any greater, except at the soil surface, but the thoughtful experimenter will try to cover the whole of the unsaturated region, down to oven-dryness if experimental technique will permit.

Plant tissue abounds in semi-permeable membranes, not perfect, so that water uptake by the roots, and transfers between cells within the plant, are governed by mixed processes, partly viscous flow under a matrix potential gradient in which all the fluid moves, carrying ions with it, and partly diffusive flow, in which only the pure solvent can move. For the present purpose it is sufficient to note that water uptake by roots from unsaturated soil becomes vanishingly small at the miscalled "wilting point" (pF = 4.2), and the same state can be produced in a saturated soil with a sufficiently high concentration of solute—the state of "physiological drought". (To give scale, sea water has a pF of 4.5, *i.e.* it has twice the limiting concentration.)

All these equations represent movement toward equilibrium, and in equation (1) work must be done against friction to maintain the flow. In general, but not always, the energy to keep a flux going comes from outside the system. A notable exception is the wetting of a dry soil. This can be done from below, and the work done in lifting the water against gravity comes from the water itself: it uses some of its "free" energy. At the top of the capillary column, the free energy decrease is equal to the increase in gravitational potential, *i.e.* per cubic centimetre it is ρgh where: ρ is the density, g is the gravity acceleration constant, and h is the height of the column. The elementary physics of the equilibrium at the top of the column yields $\rho gh = 2T/r$, where T is the surface tension of water, and r is the radius of the 'tube'. For $h = 10^3$ cm, then $\gamma \simeq 1.5\,\mu$ and $\rho gh \simeq 10^6$ ergs per cubic centimetre, or 1/42 cal cm^{-3} in heat units. Also, $\log h = \mathrm{pF} = 3.0$. This is a convenient height for general discussion. It is on the scale of the height of a tree (10 m), and it is a good general measure of the potential of water in the soil at which most of the water available for plants has been extracted. It is also the height of a water barometer column, and when it is undesirable to express large water potentials on a logarithmic scale it is convenient to use a linear scale of atmospheres. So wilting point (pF = 4.2), corresponds to a 'tension' or 'suction' of 16 atmospheres, and the work needed to remove 1 cm^3 of water against this suction is 16/42 calories. This is a trifling amount compared with what is needed to evaporate the same volume, which is near 580 calories at ordinary temperature. In nature the source of energy for evaporation processes is the sun, the radiation intensity varying with latitude, season and time of day: in middle latitudes the midday summer intensity is near 1 cal cm^{-2} min^{-1} and the mean daily summer total is near 400 cal cm^{-2}. It seems a fair inference that problems of unsaturated flow that affect, or are affected by, vegetation can be discussed without concern for energy balances, except where evaporation or condensation is involved. These are important in very dry soil, where flow across an air gap takes place as vapour (Rose, 1963*b*), and the effect is to retard the transfer.

It appears that plants can go on transpiring until the suction in the leaves is near 16 atmospheres, and then the stomata close, so sealing the outlet for water. With Van den Honert (1948), it is safe to assume that the resistance to viscous flow between the outside of the roots and the inside of the leaves is usually negligible when other resistances are important, *i.e.* in looking at the influence of plants on soil water and on soil water movement there is little risk of serious error in thinking of the roots as constant potential sinks for water. The effect of roots will depend on the volume of soil they 'occupy', and the rate they grow to occupy new volume in response to diminishing supplies of water. In general it is not sufficient to discuss soil water problems solely in terms of available water: it is necessary at times to consider accessibility too. Here are two concepts that need clarification.

III. AVAILABLE WATER AND ACCESSIBLE WATER

Agricultural experience shows that the use of water by plants occurs over a range of soil wetness between field capacity and so-called wilting point, with nothing hydrologically significant beyond. For any worthwhile study of drying processes these limits must be expressed in terms of water potentials and this is one of the reasons why study of potentail gets explicit reference in the research programme of the International Hydrological Decade. The 'available water' is usually defined as the difference in water content between soil at field capacity and soil at the wilting point, and this is satisfactory provided it is remembered first that this is a definition in terms of potentials; second that the potentail is a property at a point; and third that, if there is to be any meaningful conversion to quantities of water, the potential must be uniform over the volume of soil under consideration. Although this third condition is not likely to be satisfied in a soil on which there is active plant growth, suppose it is true throughout the depth of soil occupied by the roots. Then, in the absence of rain, the plants will remove water, producing what is frequently called a deficit of soil water—simply the 'deficit' —and, as noted, the hydrological significance of the deficit is that it is a measure of the amount of rain, or of irrigation, that has to be applied to rewet the soil to field capacity, and only when this is achieved will there be any surplus to percolate to replenish groundwater or increase stream flow. The consequences are fairly well known, and one particular example will suffice. In south-east England a relatively dry winter succeeds a dry summer perhaps once in a decade; the deficit built up in the summer is greater than the winter rainfall; there is no significant winter recharge of groundwater, and well levels continue to fall. Fig. 1 (Penman 1950) shows this happened to a chalk catchment in 1933-1934, and 1943-1944. The same concept is also being used in flood studies where attempts to allow for 'antecedent soil moisture status' are brought in.

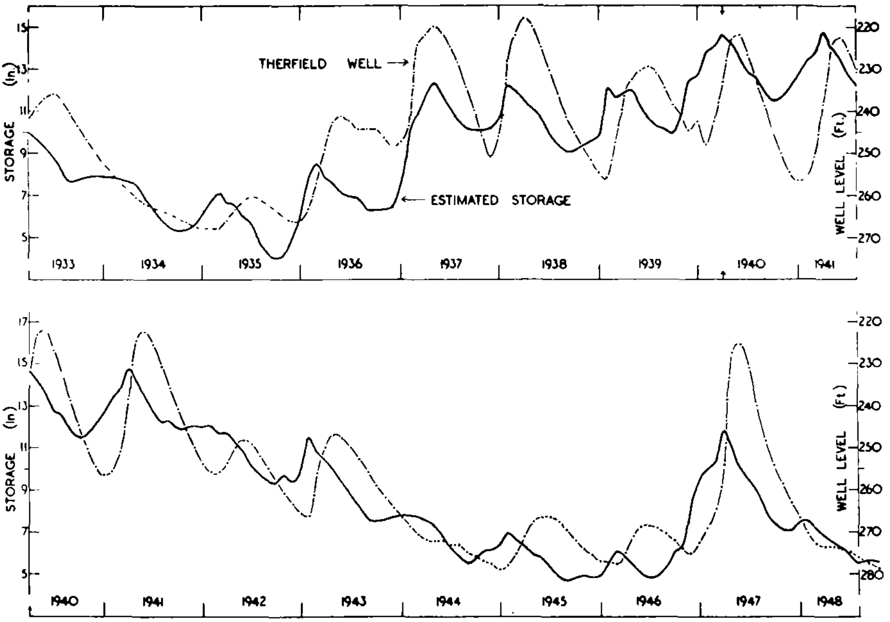

FIGURE 1. *Water balance of the Stour catchment. Full line: estimated storage from measured precipitation and stream flow, and calculated evaporation. Broken line: observed well level, on edge of catchment*

The figure also shows an estimate of the changes in stored water in the aquifer. The success or failure in obtaining agreement—after allowing for an expected phase lag—is irrelevant here: what is important is the kind of assumption that has to be made about the rate at which the soil moisture deficit increases in a period free from rain. Accepting, as many workers do, that there is a potential rate of evaporation determined by the weather, and that this is also a real rate when the soil is near field capacity, the problem is: how long during the drying process do potential and actual rates of evaporation remain equal? The answer from Veihmeyer and his collaborators is that all the water in the soil between field capacity and wilting point is equally available, and for a constant external demand the rate of evaporation is constant. Others deny this, and some assert that after a short initial period at constant rate there is an exponential decay, the rate being proportional to the amount of available water still unused. At first this sounds plausible, but for it to be true as a physical theory, first the quantity would have to be proportional to the potential (as it is in heat flow problems) and this is very far from true for soil water; and second the only important potential drop separate would have to be between the soil and the inside of the plant. This is not true either: the main resistance is between the inside of the leaves and the outside atmosphere, approaching infinity as the plant wilts. So, although an exponential curve is a good fit for some experimental results, the fit may be fortuitous.

The Veihmeyer hypothesis, on the other hand, can be defended in reason, and can be shown to work in practice when the boundary conditions associated, both explicit and implicit, are known to be satisfied. But it breaks down so often in the field that it is perhaps more useful as a guide to thought than a guide to action. One expects it to be true when the relevant water potential is that of the soil in contact with the roots, and if the roots ramify so thoroughly throughout the soil that root-to-root distances are very small, the water potential as measured by some relatively large sensor will not differ significantly from that outside the roots. Then, as Veihmeyer has shown in good experiments in a constant (or nearly constant) environment, the total water use increases linearly with time almost up to the specified limit of soil dryness. Alternatively, where the environment varies, the plot of total water loss against an estimated accumulated potential transpiration is linear over a large range. Fig. 2 (derived from Veihmeyer and Hendrickson, 1955) shows the water use by single small pine trees growing in pots,

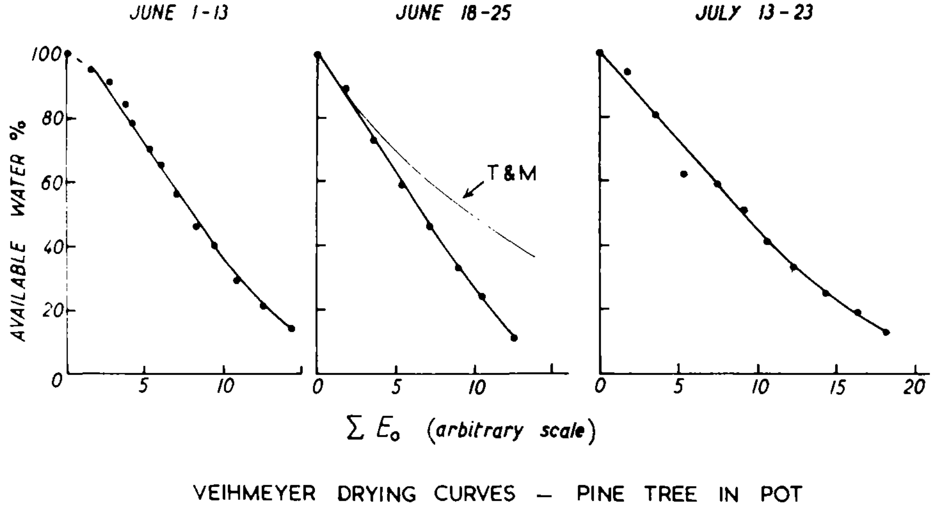

FIGURE 2. *Veihmeyer drying curves replotted against open water evaporation. "T and M" is for an exponential decay*

plotted against the contemporary evaporation values from a standard open water pan, together with an estimate on one set of data of what the water use curve would look like assuming an exponential decay: there is no uncertainty about which is the better fit. Hallaire (1954) obtained an equally good straight line in plotting accumulated water use by sugar beet against accumulated potential transpiration (Thornthwaite), over the whole of a summer in which the soil moisture deficit increased to 270 mm.

Although the issue is important in agriculture, it matters less in hydrology where optimum plant growth is not a technical objective. The important hydrological aspect of plant cover is that the soil moisture deficit has an upper limit, depending on soil and plant characters, and is reached when the plants cease to transpire. The time needed depends on the weather, and how nearly actual transpiration rate equals potential transpiration rate over the period of drying. In general, at intermediate stages, the difference between indirect estimates based on the two hypotheses briefly outlined above will rarely exceed the uncertainty in estimating either. Some of these sources of uncertainty lie in the behaviour of the aerial parts of the plant and would need to be discussed in terms of meteorological physics and plant physiology, but are outside the scope of this survey. Others are linked with soil properties and root behaviour, and the remainder of this survey will show a few examples of the way in which plant action produces unsaturation in soil profiles, based on seasonal evidence.

IV. EFFECTS OF ROOT DEPTH AND SOIL CHARACTER

Within the seasonal cycle there are daily cycles, and there is now no difficulty in finding field evidence that the diurnal pattern of water extraction is very nearly in phase with the solar radiation, and when actual rate is equal to potential rate, the daily total of evaporation is—in energy equivalent—very close to the total net radiation for the day. In contrast, field evidence of where in the profile the water comes from during the course of a day is almost non-existent. One set of observations under a barley crop (Long *et al*, 1964), using a neutron moisture meter, indicated drying of the profile between the surface and 50 cm between 08.00 h and 13.30 h with a smaller gain of water between 50 and 100 cm: between 13.30 h and 16.00 h the upper layer recovered some of its morning loss at the expense of the deeper layer. The effect may not be just an experimental accident, and laboratory experiments are in progress to test it. Theoretical interpretation will involve those concepts of water potential gradients and unsaturated conductivity that will occupy a great part of the time of this symposium. All other evidence —and there's not very much, even so— is over periods of several days, weeks or months.

At each stage in development a plant's root system occupies some definable depth of soil (usually unknown), and at field capacity the amount of available water depends on the depth so occupied, and on the moisture characteristic of the soil. The amount of this that is accessible is determined by the ramification of the roots and the hydraulic conductivity of the soil. It is sometimes helpful to describe this amount of accessible water as a 'root constant' recognising that even for a given plant it may vary from soil to soil, and that in a given soil it may change as the plant develops and grows. One example, perhaps so exceptional that it may be ignored elsewhere in hydrology, is that in the Aden Protectorate a crop of cotton can be grown to full maturity with one pre-sowing irrigation that wets the top 300 cm of the profile (Rijks, 1965): root development is sufficiently rapid for the 'root constant' to increase as fast as (or faster than) the transpiration rate. On the semi-humid highlands of Kenya some of the perennial crops develop large root systems on the deep volcanic soils: Kikuyu grass roots reach a depth of 6 metres (Pereira, 1951). During the dry season the actual rate of drying is probably close to the potential rate until all the available water is extracted. (Glover and Forsgate, 1964, confirmed the Veihmeyer hypothesis on Kikuyu grass grown in tanks 120 cm deep.) Here too are exceptional ecological conditions with a crop cover that can produce a very deep root system, and a soil deep enough to contain the root system, but the hydrology is not exceptional. To the certain benefit of the farmer, but possibly to the dismay of the water engineer, this combination of crop, soil and climate is producing the maximum possible total evaporation.

The other extreme is, of course, zero soil depth; but near the limit, and providing a practical challenge, are the eroded soils of the eastern United States where there is extensive agriculture on material not much more than 20 cm in depth. Van Bavel's (1953) studies of the agricultural hydrology of these areas shows that the nature of the crop cover is not very important: the available water is equivalent to about 5 cm of rain and the water balance can be calculated adequately by assuming it is all transpired at the potential rate, and then there is no further evaporation until the profile is rewetted.

Between the extremes is the very wide range of conditions in which the soil depth is sufficient to contain normal root growth. For short crops (up to about 100 cm tall) there is reason and considerable evidence to suggest that, during the period of full leaf cover, the potential transpiration rate is almost independent of the nature of the crop, and exposed side by side to the same weather different crops will dry out the soil at the same rate so long as the deficit is less than the root constant. As a minor but interesting demonstration, two grass species in their first year used the same amount of water between the end of June and the middle of September 1964 at Rothamsted (Long and French, 1967).One, Timothy, took nearly all of it from the top 40 cm of the profile while the other, Meadow Fescue, took less from above and more from below 40 cm. (The measurements were made at about 10 day intervals with a neutron moisture meter, with a sampling tube in each of four replicate plots.)

Expectation is that in a period of drought the deeper rooted crop of the pair would go on transpiring longer at or near the potential rate and build up a bigger deficit. This kind of contrast—and behaviour—occurs more usually in comparing different plant species, notably in grass/tree comparisons. In general the root constant for trees is greater than that for grasses, and selecting only one piece of quantitative evidence, Croft and Monninger (1953) found in Utah, that experimental plots under trees continued to lose water for about one month after those under grass had stopped evaporating, and the excess withdrawn was equal to the available water in the extra depth of soil profile occupied by the roots of the trees. There have, of course, been many attempts to exploit this kind of contrast in catchment management, some of them reviewed by Colman (1953). There are not so many tree/tree comparisons, but ignoring complicating factors to be stated later, in general the tree/tree comparison tends to show equal rates of water use, *i.e.* the building up of equal soil water deficits in the same climate. Again, choosing only one area as a source of quantitative evidence, by periodic soil samplings 1948-1961, (summarised by Pereira *et al*, 1962) down to 10 feet, relative rates of water use by different kinds of cover were estimated for periods free from through drainage. The area is in East Africa, at about 3000 m altitude in the Aberdare mountains, and the conclusion was 'equal consumption by 120 feet high, 26 years old Radiata pine; 50 feet high, 16 years old Monterey cypress; 30 feet high, 10 years old 'shamba' planted Patula pine (after clean weeding had ceased); and from the undisturbed indigenous thicket'. Of several catchment management experiments started in 1957, one is in the same area. (First full report, on first three years, by Pereira *et al* 1962: latest interim report, on first seven years, in *E.A.A.F.R.O. Annual Report* for 1964.) Bamboo forest was replaced by softwood plantations with an initial phase of vegetable growing among the newly planted softwoods (the 'shamba' system). A control valley was left uncleared, and both areas were extensively instrumented to obtain detailed hydrological balance sheets and adequate weather records to test possible theoretical ideas. During the first year the very sparse crop cover of the cleared valley transpired very much less than the control, *i.e.* the water yield was greater, with more flood discharge and some erosion. As the cover closed in the second and third year the differences diminished, and over the last four years for which records exist the measured mean annual evaporation was 105 cm for the control and 104 cm for the replanted area.

The complicating factors may be differences in plant physiology between one cover and another, differences in aerodynamic properties of the crop 'surfaces', differences in interception of rain, and differences in radiation balance. All of these, and particularly the last, may have been operational in one of the Coweeta experiments (Hibbert, 1966). Catchment 13, area 16 ha, was cleared of mixed hardwood trees in the winter of 1939-1940, so producing a shallow hole in the forest canopy. Stream flow was very much greater in the following year, but the 'gain' rapidly decreased in the next few years while resprouting was restoring a complete crop cover, and then more slowly as the new vegetation steadily filled the shallow hole. (Tree heights are not given in the paper.) The inverse aspect of changed radiation balance is revealed in an experiment by Van Bavel *et al* (1963). They measured the transpiration rate of Sudan grass 100 cm tall on a one metre square sample in a large plot: then the surrounding plants were cut down to about 15 cm and, in equivalent weather, the transpiration rate was measured again. It increased by 50 per cent.

Here is a source of a warning in designing and interpreting experiments on the degree of unsaturation that can be produced by transpiring crops. If a square plot of side l projects above its surrounding by height h, the extra fractional area taking part in radiation exchanges is $4h/l$, and if $l = 50h$ then the increase in area is 8 per cent. Taking this as an acceptable degree of error, then for a crop 1 m taller than its surround, l should be 50 m, *i.e.* the plot area should be at least 1/4 hectare: if the crop projects by 10 m then the minimum area should be 25 hectares, The changed aerodynamic character will also produce an increased evaporation rate .

V. EFFECTS OF SEASONAL COVER

So far the discussion has been of a crop cover doubly continuous, completely shading the ground, and evergreen. Important differences in plant/soil water relationships may arise when either of these conditions is varied, as they are for annual agricultural crops, and for perennial deciduous crops. While the soil is bare, and for some time after the emergence of an annual crop, the evaporation rate is nearly the same as from a cropped surface as long as the bare surface is wet. Depending on the weather, this condition usually lasts for only a few days after rain or irrigation, and then the evaporation rate rapidly decreases (see D. A. Rose, this symposium). The effect is that total evaporation from bare soil is very closely correlated with total rainfall when rainfall frequency is small enough to permit surface drying between falls, and independent of rainfall when rainfall frequency is great enough to keep the soil surface continuously wet: in northwest Europe these are summer and winter conditions respectively.

It is very difficult to define when crop cover is 'complete' and each worker has to make his own guess: the succeeding period of development, in which estimates of potential transpiration might be used safely, will come to an end—or may come to an end—as the crop matures, and possibly in very different ways. The preharvest water extraction by sugar beet, potatoes, and cereals sets three separate problems in agricultural hydrology.

There are very few sources of information on evergreen/deciduous tree contrasts: fortunately, the best is very good. At Castricum, on the coastal dunes of the Netherlands, four lysimeters were set up on different kinds of dune vegetation in 1942, each being 25 m square with a water table maintained at 2.25 m below the soil surface: with a few possible exceptional periods the trees on two of these (III and IV) have probably never experienced any significant check to transpiration because of lack of soil water. It took a long time for the trees to grow to almost the same height as those of the surrounding area, and the best long period comparison is for recent years. The results for 1955-1964, kindly supplied by Dr. L. J. L. Deij of the Royal Netherlands Meteorological Institute, were used in a paper on forest hydrology (Penman, 1966) and are summarised in table 1. From the measured water-balance the mean annual evaporation was 500 mm from lysimeter III (Deciduous trees: oak, alder and birch), and 655 mm from lysimeter IV (Conifers: Austrian fir). Arbitrarily assuming the period of full leaf cover on lysimeter III is May to October and that transpiration is at the potential rate then, but is zero for the remaining six winter months; and assuming the same aerodynamic factors and the same reflection coefficient for both kinds of trees (0.15), meteorological estimates were made of the expected summer evaporation and winter evaporation from the two areas. From the individual monthly totals of precipitation and drainage, with some difficulty and considerable uncertainty, more direct estimates were made of the same quantities. The two sets of estimate are in table 1. Discussion of the sources of error in the two kinds of estimates would be needed before making safe inferences. The most certain is that in winter transpiration is not the only important form of evaporation, and under deciduous trees the water balance of the soil has a significant component contributed by evaporation from the soil surface and from bare trunks, branches and twigs; for the conifers, intercepted water on the leaves behaves in the same way. Rutter (1966), among others, has made good progress in measuring the amount of intercepted water and the role it plays in the water balance of the soil.

TABLE 1. Estimated summer and winter evaporation from deciduous trees (III) and conifers (IV) Castricum 1955-1964 (mm per period)

	May-October		November-April		Year	
	III	IV	III	IV	III	IV
Meteorological	476	476	0[1]	102	476[1]	578
Direct	410	465	90	190	500	655

[1] Assuming zero winter evaporation

VI CONCLUSION

The effects of vegetation on the water content of the unsaturated zone depend on the plants themselves, on the soil, and on the weather, and although ultimately all may be expressed in physical terms, it is helpful to recognise biological and non-biological components. Seasonal or long period changes in plant morphology or physiology affect water demand and water use, and as a crop grows and develops its behaviour as a surface affects radiation and energy exchanges and the fate of incoming precipitation. Human intervention can modify some of these factors, and there is now some qualitative understanding of what modifications might do in affecting crop harvest and water harvest. Soil nature, structure and depth are also important, but soils are much less amenable to management, and their variability from site to site poses rather difficult problems in getting areal averages of relevant parameters. The climate of a given area may have determined the nature of the soil, it certainly determines the nature of the vegetation the soil can support, and interacting with the soil, the geology, the topography and the vegetation the climate determines the hydrology.

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Discussion

P.E. RIJTEMA:

The concept of available water is dangerous when a large supply of water is present from below the root zone. In fact this concept only holds for soils in which the sub-soil does not contribute to the water supply *e.g.* in coarse sandy sub-soils with a ground water table at great depth.

H.L. PENMAN:

I stated in the paper that the concept is a useful guide to thought, always: I think this is true.

P.E. RIJTEMA:

Fig. 2 of your paper does not prove the concept of equal availability of soil moisture between field capacity and wilting point, as the data concern results of pot experiments. Further no reference has been made between the amount of available water and the suction. In particular under conditions of pot experiments, the root density is very high and if the main part of the available water is present at low suctions, and if transpiration is not extremely high, one should not expect any reduction in transpiration.

H.L. PENMAN:

I disagree: the system behaved as predicted (very closely), so I accept the evidence as supporting the hypothesis on which the prediction was made.

F.F.R. KOENIGS:

Veihmeyer's experiments were conducted with pines, well known for their ability to withstand drought. Will other kinds of plants like lettuce not show signs of wilting or retarded growth at lower pF?

H.L. PENMAN:

Almost certainly 'yes'. One of the reasons for doing irrigation experiments is to find out when growth is checked.

G.H. BOLT:

I should like to voice a slight objection ot the statement of Dr. Penman that the use of equation (2) might be safer than that of equation (1). Both are susceptible to misinterpretation if applied without proper knowledge of the system. That is, one should realize that in equation (1) the potential gradient and the transport coefficient must refer to the same process, preventing one to use the gradient of the total potential for describing the sum of "mass" and "diffusion" flux. However, the concentration gradient is much more open to misinterpretation, as there are many ways of defining concentration. The one referred to here, *e.g.* volume moisture content seems to be a very poor one for the purpose of constructing equation (2), as it would suggest that water might flow between saturated layers of different porosity, whereas it would not flow in a saturated homogeneous system. Obviously diffusive flow of water, on the other hand, will follow gradients of *e.g.* mole fractions of water, rather than volumetric moisture content. In fact I would prefer to look at equation (2) as derived from a potential equation of the form $f_D = (-Dc/RT)$ $(d\mu/d\psi)$ which for ideal solutions only degrades into Fick's equation. I would advise to use solely equation (1), with the warning that the gradients of the proper potential gradients must be selected for the different types of fluxes, each combined with appropriate transport coefficient.

H.L. PENMAN:

My comment was provoked by the somewhat unexpected success some workers have had in using moisture content in the flow equation and the need to remember what it means.

R. SUNKEL:

Recent investigations on aggregates from clayey soils, published in *Zeitschrift für Pflanzenernährung, Düngung und Bodenkunde* (1965), have shown, that when drying the aggregates at different suctions, water is replaced by air only at more than 15 atmosphere suction, so that plant roots hardly can take off this water.

H. L. PENMAN:

This information is very welcome and the reference too.

O. KLAUSING:

What is your opinion about the possibility of characterization that soil moisture range, before permanent wilting point will be reached, but incipient drying is observed?

H. L. PENMAN:

Before wilting the plant may be responding to water stress by change in stomatal opening. This 'control' of transpiration must at the same time 'control' growth. It is a matter for experiment to determine how far this phase of growth is concentrated in the roots rather than the tops. There is some evidence that this is so and it would seem to be a help in making more water accessible to the plant.

P. E. RIJTEMA:

I can very well agree with Dr. Penman's statement that a reduction in transpiration is controlled by stomatal opening. With regard to this I should like to know Dr. Penman's openion about the concept of Gardner and Ehlig concerning the uptake of water by plant roots. From our experiments it could be shown that a close correlation is present between the reduction in transpiration and the suction in the leaves, which in turn is related to transpiration, suction in the root zone, the transport resistance for liquid flow in the plant and the transport resistance in the soil of the root zone.

H. L. PENMAN:

My recollection is that the paper of Gardner and Ehlig did not alter any of my preconceived ideas, but I must read it again.