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EVAPORATION FROM FORESTS

by

J B Stewart

SUMMARY

A review of the literature on research into the evaporation from forests suggests that the biological factors as well as the meteorological conditions are very important in controlling the evaporation from a forest, even when water is readily available. With the general object of studying the factors controlling the evaporation, a project has been set up in the forest near Thetford in East Anglia. The specific objectives of the Thetford Project are to compare the rate of evaporation of transpired water with the estimated rate of evaporation calculated on the assumption that the air in contact with the leaves is saturated and to assess the importance of the downward transfer of sensible heat of the air in comparison to solar radiation for supplying energy for evaporation of intercepted precipitation.

The actual evaporation will be computed from micrometeorological measurements of the energy budget and the temperature, humidity and wind profiles. The measurements, made by instruments mounted at heights up to 20 metres above the canopy, will be recorded by an automatic data acquisition system on punched paper tape, which will be directly compatible with the computer used for the data analysis.

CONTENTS

1. INTRODUCTION

The work of the Institute of Hydrology at Wallingford is primarily to study the effects on the hydrological cycle of changes in land use, in particular, changes from grassland or moorland to forest. The two aspects of the hydrological cycle most affected by changes in vegetation are the evaporation, and therefore water yield, and the occurrence and severity of flooding. To study these effects a number of experimental catchment areas have been instrumented. In some cases the land use of the catchment areas will be altered during the investigations and in other cases catchment areas with differing vegetation are compared. The interest in the effects of changes of land use has arisen because there is a considerable afforestation programme being carried out in the upland areas of the United Kingdom. These areas were previously used as grazing land for sheep, but this is now becoming uneconomic due to increasing labour costs. Since these upland areas also provide much of the water supplies for this country, it is important to have the basic knowledge on which to assess the economics of afforestation of these areas.

Before designing and setting up an investigation into the evaporation from various types of vegetation, a review of the literature was undertaken from which two facts soon became apparent. Firstly, relatively little is known about the evaporation from forests (Leyton *et al.*, 1967a), whereas the evaporation from low vegetation has been studied in great detail (eg Pasquill, 1949; Rider and Robinson, 1951; Pruitt *et al.*, 1967; Swinbank and Dyer, 1967) and its evaporation can be estimated satisfactorily from the Penman formula as long as there is a plentiful supply of water (Penman, 1963, p.34). For this reason, therefore, it was decided to concentrate the work on forests. Secondly, that short period measurements of evaporation would be necessary so that the complex inter-relations between the many variables could be unravelled. The implication was that evaporation could not be estimated usefully from water balances, which have to be made for periods of months to be reasonably accurate, and therefore micrometeorological measurements of evaporation would be required. To be able to undertake this type of experiment it would be necessary to have a uniform area, ie a generally flat area and with trees of similar height. Both these requirements ruled out making the measurements in one of the Institute's existing catchment areas and therefore the investigation is being set up near Thetford in East Anglia, where there is a very extensive forest covering slightly rolling country.

2. THE EVAPORATION PROCESS

2.1 THE GENERAL CASE - EVAPORATION FROM A FREE WATER SURFACE

Water evaporates into the surrounding air whenever the number of molecules leaving the surface exceeds the number returning. This occurs when there is a decrease in the concentration of water vapour away from the evaporating surface. If there is no external source of energy to supply the latent heat of vaporisation, the energy will be obtained from the sensible heat of the liquid water, thereby reducing its temperature. Since this will cause the vapour pressure of the air in contact with the water surface to be reduced, the vapour pressure gradient will also be decreased. This process will continue until the temperature of the liquid water has been reduced to the dew point temperature of the ambient air and consequently the vapour pressure gradient and the rate of evaporation will have become zero.

If energy now becomes available from an external source, for example in the form of solar radiation, this will be absorbed by the water, the temperature of which will then rise above the dew point of the ambient air. With the corresponding increase in vapour pressure, a gradient will be set up and evaporation renewed. With the onset of evaporation, some of the incoming energy will be passed into the air as latent heat and this will cause the temperature of the surface to fall. Also, some the energy will be removed as sensible heat by conduction to the air because a temperature gradient has been established. The surface will eventually attain an equilibrium temperature, at which the loss of energy from the surface to the surrounding air by conduction of sensible heat and by evaporation balances the input of energy from the external sources. The actual temperature will depend on the rate of input and removal of energy.

The rate of removal of energy will be a function of the gradients of water vapour and temperature and of their transfer coefficients, the latter being related to the wind velocity and the aerodynamic roughness of the surface. The proportion of the available energy which is used for evaporation will depend on the ratio of the gradient of water vapour to that of temperature, when the equilibrium state has been reached. Under the usual meteorological conditions, ie an unsaturated air stream passing over the surface, more of the incoming energy is changed into latent heat than into sensible heat. This will be accentuated as the eddy transfer coefficients become larger, because the consequent lowering of the equilibrium surface temperature will affect the gradient of temperature more than the gradient of water vapour, when the air above the surface is unsaturated.

2.2. EVAPORATION FROM A FOREST

This can be divided into three components and can be expressed by the equation:

$$E = E_I + E_T + E_S \qquad (1)$$

where E is the total evaporation for the period

- E_I is the amount of intercepted water evaporated
- E_T is the amount of transpired water evaporated and includes that from any undergrowth as well as from the trees
- E_S is the amount evaporated from the soil and litter layer.

These components will be dealt with separately because different factors are important.

Evaporation of Intercepted Precipitation

Some of the gross precipitation falling on the forest is intercepted by the vegetation and never reaches the ground, but is returned to the atmosphere by evaporation - the amount intercepted depending on the storage capacity of the vegetation and the temporal distribution of the rainfall. Since the intercepted precipitation is in the form of a free water surface on the leaves and branches of the trees, it evaporates by the process described in Section 2.1. Because a forest is aerodynamically rougher than low vegetation, the transfer coefficients are larger and therefore, as pointed out above, a larger proportion of the incoming energy will be used for evaporation than in the case of smoother vegetation.

The presence of intercepted water on the leaves prevents, or at least severely reduces, the rate of evaporation of transpired water from the vegetation and therefore intercepted precipitation should not necessarily be considered as a complete loss from the runoff of the area. However, if the rate of evaporation of intercepted precipitation is greater than the rate of evaporation of transpired water, interception will reduce the runoff, the reduction being proportional to the intercepted amount and the difference between the rates of evaporation of intercepted and transpired water. If the difference between the rates of evaporation is large, the temporal distribution of rainfall becomes an important factor in determining the overall evaporation.

Evaporation of Transpired Water

Whereas the rate of evaporation of intercepted water depends only on the meteorological conditions, the rate of evaporation of transpired water also depends on biological processes and the availability of water from the soil. The effect of these other variables is to reduce the vapour pressure of the air immediately in contact with the leaves, below the saturated value with respect to the temperature of the leaves and therefore the evaporation will proceed at a lower rate than that determined wholly by the meteorological conditions. To compensate for the lower rate of removal of energy from vegetation by the evaporation process a higher equilibrium surface temperature is attained and the excess energy is removed as sensible heat. Plant physiologists consider that the flow of water from the soil into the atmosphere via vegetation is most likely to be impeded at the soil-root and at the leaf-atmosphere interfaces. These resistances to water flow probably vary considerably depending on the meteorological and soil conditions.

Evaporation from the Soil

Evaporation from the soil of a forested area is generally a very small component of the total evaporation unless the canopy is very open, because little energy can reach the ground.

3. RESULTS FROM PREVIOUS STUDIES

Most of the quantitative information on the evaporation from forests has been derived from measurement of the water balances of forested catchment areas. Since, to obtain a reasonable accuracy it is necessary to compute a water balance by considering a long period (normally a year), only the total evaporation over the period can be obtained. This means that it is impossible to evaluate the effect of certain parameters. In particular, it is not possible to determine the relative importance of the two major components, ie the evaporation of intercepted and transpired water. From measurements of water balances it generally appears that qualitatively the evaporation from a forested area is similar or slightly more than that from a grassed area but there has been very little quantitative agreement between the results (Hibbert, 1967). In some of the more detailed studies, measurements of the total amount of precipitation intercepted have been made and during the winter months this has been found to exceed the amount that could be evaporated by the net radiation by large amounts (Rutter, 1963; Patric, 1966; Helvey, 1967; Leyton *et al.*, 1967b).

In recent years there have been a number of experiments using single trees (Thorud, 1967) or branches (Rutter, 1967), where the rate of evaporation of intercepted precipitation has been compared to the rate of evaporation of transpired water under the same conditions. It has been found that the former was many times faster than the rate of evaporation of transpired water. These results can only give a qualitative indication of the situation in a forest. However, Rutter (1967) has carried out similar studies in a forest canopy and obtained similar results.

Some important conclusions can be drawn from these results:

(1) That the rate of evaporation of transpired water from trees must be considerably affected by plant and soil factors, otherwise it would be similar to the rate of evaporation of intercepted precipitation.

(2) It appears that in winter at least another source of energy must be contributing to the evaporation of intercepted precipitation; probably there is a downward flux of sensible heat providing energy for evaporation.

(3) It was shown in the description of the evaporation processes that loss due to intercepted precipitation depended on the total amount intercepted and on the difference between the rates of evaporation of intercepted and transpired water. Therefore it would appear that the total evaporation from a forested area will depend markedly on the temporal distribution of precipitation. Since the evaporation from low vegetation does not depend on this factor, it would be expected that evaporation from a forested area could vary considerably from that for a grassed area.

(4) From the experimental and theoretical work it appears that the following will be the most important parameters:

Meteorological Variables

The net radiation.

The characteristics of the ambient air above the forest, ie its temperature and humidity.

The transfer coefficients of heat and water vapour.

Biological Variables

Resistance to flow of water from soil into the root.

Resistance to flow of water within the plant.

Resistance to flow of water from within the leaves to the atmosphere.

Soil Variables

Soil moisture tension.

Soil temperature in the rooting zone.

In turn these parameters will depend on other variables as well as on characteristics of the experimental site and its vegetation.

4. THETFORD PROJECT

4.1 OBJECTIVES

The main objectives of this project are:

(i) The confirmation and elucidation of the difference between the actual rate of evaporation of transpired water and the estimated evaporation based on the assumption that the leaves can be considered as free water surfaces.

(ii) The investigation of the importance of the downward transfer of sensible heat of the air to provide the latent heat for evaporation of intercepted precipitation, in comparison to the energy supplied by solar radiation.

(iii) To determine whether the rate of evaporation varies across the forest due to horizontal gradients of humidity, temperature and wind speed.

(iv) To determine which parameters besides the meteorological factors are of major importance in controlling the evaporation from a forest.

Objectives (i) and (ii) will be studied in phase I and the others in phase II. If these objectives are successfully attained it should be possible to estimate at least qualitatively, the effect of afforestation on the water yield from a catchment area by comparing the results of this project with those from investigations into the evaporation from low vegetation.

4.2 METHOD OF ANALYSIS

The basic measurements will be taken every half minute and then combined to give 20 minute average values which will be used in the relevant equations (see the next subsection) to calculate the rate of evaporation. To separate the effects of the many parameters, the results will be divided into various periods during which some of the parameters either have little or no effect or are constant. Thus for periods when the leaves are wet after precipitation, the rate of evaporation only depends on the meteorological variables. Under these conditions any occurrence of a downward flux of sensible heat can be readily determined and its relative importance as a source of energy assessed. Also, the rate of evaporation can be compared to the potential rate predicted by the Penman formula using measurements of the relevant variables made above the forest. Using the measurements made during periods when the leaves are wet, an empirical relationship between the rate of evaporation and the meteorological variables can be determined. This empirical relationship will then be used to estimate the rate of evaporation, which would occur if the leaves were wet, for comparison with the actual rate of evaporation when the leaves are transpiring. For periods when the rate of evaporation of transpired water is not limited by the availability of water from the soil, the effects of the impedances to water flow through the trees will be evaluated. As the final stage in this analysis, it may be possible to assess the effect of soil moisture depletion on the rate of evaporation of transpired water.

An independent check on the micrometeorological measurements of evaporation can be obtained from measurements of the amount intercepted by the forest in individual rainfalls. From the measurement of the amount intercepted and of the time taken for it to be evaporated, the rate of evaporation can be obtained and then compared with the micrometeorological measurement.

4.3 METHODS OF MEASURING THE EVAPORATION FROM FORESTS

As explained in Section 2, the rate of evaporation depends primarily on the availability of energy, and therefore the rate of evaporation can be calculated most satisfactorily by measuring the components of the energy budget. The energy budget can be expressed by the equation:

$$\underline{R}_n = \underline{G} + \underline{H} + \lambda\underline{E} + \underline{S} \tag{2}$$

where $\underline{R}_n$ is the net all-wave radiation flux

$\underline{G}$ is the soil heat flux

$\underline{H}$ is the sensible heat flux

$\lambda\underline{E}$ is the latent heat flux

$\underline{S}$ is the forest heat storage

All the components except $\underline{H}$ and $\lambda\underline{E}$ can be measured readily or estimated. To obtain the rate of evaporation $\underline{E}$ ($= \frac{\lambda E}{\lambda}$ where λ is the latent heat of vaporisation of water) from the above equation the flux of sensible heat has to be measured by another method or the available energy has to be partitioned into the latent and sensible heat fluxes using the Bowen ratio.

The Bowen ratio β is the ratio of the flux of sensible heat to that of latent heat and by use of the aerodynamic equations for these fluxes becomes:

$$\beta = \frac{\underline{H}}{\lambda\underline{E}} = \frac{c_p \, \rho \, K_H \overline{\frac{\partial\theta}{\partial z}}}{\lambda \, \rho \, K_E \overline{\frac{\partial q}{\partial z}}} \tag{3}$$

where $\overline{\frac{\partial\theta}{\partial z}}$ and $\overline{\frac{\partial q}{\partial z}}$ are the mean gradients of potential temperature and specific humidity respectively and ρ and c_p have their usual meanings of density and specific heat of air at constant pressure.

For finite difference in height Δz

$$\beta = \frac{c_p K_H \Delta\theta}{\lambda K_E \Delta q} \tag{4}$$

It has now been shown experimentally that the transfer coefficients for sensible heat K_H and water vapour K_E are equal over a wide range of conditions from neutral to highly unstable (Dyer, 1967). However, it is not known whether this is still true under stable conditions, for example, when there is a downward transfer of sensible heat to supply the energy required for evaporation. Having measured the Bowen ratio, it is substituted in the following equation, which is obtained by re-arranging equation (1):

$$\underline{\lambda E} = \frac{\underline{R}_n - \underline{G} - \underline{S}}{1 + \beta} \qquad (5)$$

and this can be solved to give the rate of evaporation.

As an alternative to using the Bowen ratio, the sensible heat flux can be calculated by the aerodynamic or eddy correlation methods. The great advantage of using these direct measurements of the sensible heat flux instead of the Bowen ratio, is that no measurements of the humidity gradients are required. Generally, the instruments used to measure the humidity gradients are the most inaccurate and unreliable of any micrometeorological system.

The aerodynamic equation for the flux of sensible heat is:

$$\underline{H} = c_p \rho u_*^2 \frac{K_H \overline{\frac{\partial \theta}{\partial z}}}{K_m \overline{\frac{\partial u}{\partial z}}} \qquad (6)$$

where u_* denotes the friction velocity, K_m the transfer coefficient of momentum and $\overline{\frac{\partial u}{\partial z}}$ the average wind speed gradient.

Strictly speaking, this equation only applies under conditions of no advection. To enable the equation to be solved the following further assumptions have to be made: that the transfer coefficients of heat and momentum are equal and that the atmosphere is at or near neutral stability. Then the equation becomes:

$$H = c_p \rho k^2 \frac{(U_2 - U_1)(\theta_2 - \theta_1)}{\left(\log_e \frac{z_1 - d}{z_2 - d}\right)^2} \qquad (7)$$

where k is von Kármán's constant, d is the zero plane displacement and the subscripts 1 and 2 refer to the heights at which the measurements are made.

In practice the atmosphere is rarely at neutral stability and the ratio of K_H to K_m appears not to be even constant (Swinbank and Dyer, 1967), but to vary with atmospheric stability.

However, $\underline{H}$ is generally considerably smaller than $\lambda\underline{E}$ and therefore a larger error is permissible in $\underline{H}$ for a given error in $\lambda\underline{E}$.

Theoretically it would be preferable to measure the sensible heat flux by the eddy correlation technique, where the instantaneous vertical flow rate of the air is related to its instantaneous temperature. However, very sophisticated instruments and data logging systems are required, because the very high frequency eddies must be sampled and recorded, and at present no commercial equipment is available.

The main disadvantage of the energy budget methods is their dependence on an accurate estimate of the net radiation. Since the magnitude of the long-wave components of the net radiation are comparable to that of the short-wave components and the accuracy of calibration for the long-wave components is much poorer than that for the short-wave component, the accuracy of the measurements of the net all-wave radiation is much lower than that of solar radiation and this affects the accuracy of the evaporation measurements.

The evaporation can be estimated directly by the aerodynamic method using an equation similar to that for sensible heat, but similar dubious assumptions have to be made and generally the values for the evaporation will be so inaccurate that they are virtually useless for this work.

In the case of the eddy correlation technique which theoretically can also be used to give a direct measurement of the evaporation, no sensor has yet been developed to measure humidity fluctuations which has a sufficiently rapid response to give accurate results (Dyer and Maher, 1965).

4.4 INSTRUMENTATION AND DATA LOGGING

In general, conventional micrometeorological sensors will be used to make the necessary measurements. However, the sensors will have to be positioned at much greater heights above the vegetation than in the case of relatively smooth surfaces, such as short grass, because of the spatial variability of a forest canopy. This requires a sturdy tower to support the sensors at heights up to 30 m and to allow maintenance to be carried out; it also creates further difficulties due to the effect of the tower on the environment and necessitates investigations to ensure that the sensors are beyond the influence of the tower.

For some of the measurements, for example of radiation, it may be necessary to use sensors which can scan automatically a large area of vegetation and thus obtain a value representative of the general area.

To determine whether evaporation of intercepted or transpired water is occurring, an indication of the wetness of the leaves will be obtained by measuring the electrical resistance between pairs of wires wound round the leaves. If there is a significant difference between the rates of evaporation of intercepted and transpired water, the surface temperature measured by an infra-red thermometer can also be used as an indicator, because a decrease in the rate of evaporation has to be compensated by an increase in the surface temperature if the other variables remain constant.

Separation of the various components of the total evaporation such as the evaporation from the soil or litter layer and from any undergrowth, will be obtained by using sensitive weighing lysimeters.

From the outset, the experiment has been designed on the basis of an automatic data acquisition system to record the data on some medium which is directly compatible with the computer used to analyse the data. At the present time a system incorporating a small computer on site is being actively considered. The main use of the computer would be the programming of the data acquisition and initial condensation of the original data to give five minute or longer period averages. Besides carrying out these primary tasks the computer could do some analysis in real time and these results would then provide a means of monitoring the accuracy of the data from the sensors.

4.5 EXPERIMENTAL SITE

Valid measurements of the rate of evaporation using micrometeorological methods, depend on measurements above a site which approximates to an infinite uniform plane. In practice, the site will be suitable if it provides a fetch over a uniform area of at least one hundred times the height to which the measurements are to be made. To fulfil these requirements an extensive area of forest on flat ground (or on ground of uniform slope) is necessary. Such a site was found near Thetford in Norfolk where there is a very large area of forest covering a total area of approximately 200 km^2. The site for the instrument tower is near the centre of one of the three main blocks of which the forest is composed. This block, which covers an area of about six by ten kilometres, varies in elevation by about 20 m. The forest is planted in sections with areas of 10 to 20 hectares each, divided by rides running between them. Most of the forest was planted between 1928 and 1932 with Corsican and Scots Pine, which have now attained a height of approximately 15 m and are growing at a rate of less than half a metre per year.

5. PRESENT POSITION

A number of meetings were held at the Institute of Hydrology and at the Meteorological Office to discuss the proposed research programme. Besides the members of the Institute, these meetings were attended by Drs Pasquil and Rider and Messrs Blackwell and Grant of the Meteorological Office, Professor Rutter of Imperial College, Dr Drennan of University of Reading, Dr Monteith of Rothamsted Experimental Station, Dr Leyton of Oxford University, Dr Davis and Mr Bose of Southampton University and Mr Green of NERC. One of the results of these meetings has been the offer by Professor Rutter to co-operate in this research. Under an NERC grant two Research Assistants directed by Professor Rutter will study the biological factors affecting the evaporation from a forest. This work is expected to begin in the autumn of 1968.

In September 1967 a 32 m high instrument tower was erected in the forest with a mobile laboratory and a portable generator set installed near its base. The area surrounding the tower was planted in 1931 with Scots Pine trees which have now attained a mean height of 14.7 m with 75% having heights between 13.7 m and 15.8 m. The average spacing between the trees is 3 m.

Much of the work so far has been into the evaluation of various sensors and the method of supporting them on the tower. A preliminary study of the effect of the tower on measurements of wind speed showed than an anemometer mounted 5.5 m upwind of the tower gave a wind speed about 3% higher than an anemometer mounted only 1.5 m upwind of the tower at the same height. Previous work suggests that the effect of the tower on measurements of wind speed will be less than 1% if the anemometers are mounted about 5 m from the tower. So that reliable wind measurements can be obtained in any wind direction, two anemometers will be mounted either side of the tower at each height.

To eliminate interference between the various sensors it has been decided to use two towers. One tower will support the anemometers and the other tower will carry the other instruments. The second tower was erected in May 1968 about 45 m north west of the first tower.

Preliminary measurements of the wind profile have suggested that the zero plane displacement d is about 11 ± 1 m and that the roughness length z_0 is about a metre. For comparison the typical value of z_0 for a grass surface is about a hundredth of a metre.

To intercalibrate the anemometers used for measuring the wind profiles, a calibration rig was installed near the Meteorological Site at Wallingford. Five anemometers can be exposed at the same time and it was found that individual anemometers could be as much as $\pm$ 5% from the mean of the five, using the wind tunnel calibrations.

To obtain a better understanding of the transfer processes above a forest, measurements of the small scale turbulence structure were made by Dr. Davis of the Institute of Sound and Vibration Research, University of Southampton, using his elaborate hot wire anemometer system. The instruments have a very rapid response and are capable of measuring eddies with dimensions down to a tenth of a metre. Though there were some difficulties experienced with interference in the power supply from the portable generator set, the measurements of the velocity spectrum showed that there was a considerable component of the turbulent energy at the highest frequencies. Work is going on to remove any interference from the power supply and then it is hoped to make further measurements with Dr. Davis' equipment.

An assessment has been made of instruments to measure humidity gradients. Tests were carried out under field conditions using an Assman psychrometer as a standard. Little progress has been made and no suitable device has yet been found. Further instruments are to be evaluated when they have been delivered.

To measure the gross precipitation falling on the forest it has been decided to install raingauges in suitable natural clearings in the forest rather than use raingauges mounted at canopy height, because of the possible large errors caused by the wind flow over mast mounted gauges. To choose suitable sites ten gauges have been installed in clearings and rides within a small area surrounding the instrument tower. By studying the records from the raingauges in relation to their siting, the size of clearing necessary to obtain accurate measurements will be obtained.

A system made by Hewlett-Packard for measuring temperature was delivered at the end of May 1968. Each probe contains a temperature sensitive quartz crystal, whose frequency is compared to a standard oscillator and the difference in frequencies is measured by a counter with a digital output. The system allows, at present, ten probes to be interrogatedin turn and the temperatures and channel identifications printed out on paper tape. Because changes in temperature are detected by the quartz crystal as frequency changes, the accuracy is unaffected by stray resistances or voltages as would be the case if the more usual resistance units or thermocouples were used. Also, the use of small amplifiers can extend the distance from the probes to the counter indefinitely. Various radiation shields for the temperature probes are at present undergoing tests to determine the most effective combination of shield and aspiration rate for reducing the radiation error to an acceptable level.

6. CONCLUSIONS

To estimate the effect of afforestation on the water yield of catchment areas, the total evaporation from a forest area has to be predicted for comparison with that from grassland or moorland. A study of the literature has shown that firstly, few measurements of evaporation from forests have been made and secondly these few experiments have shown that besides the meteorological factors biological factors are very important in controlling the evaporation.

To study the processes involved in the evaporation from an extensive area of forest, a micrometeorological and plant physiological project has been set up in Thetford Forest in East Anglia. At present the instruments and their mountings are being constructed and their performance in use over the forest is being evaluated.

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