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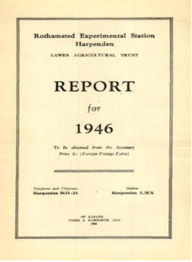

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H. L. Penman

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By H. L. Penman

Introduction: published work up to 1944

Evaporation is a very widespread phenomenon in nature and is largely beyond human control. At one extreme there is large-scale evaporation from the oceans, upon which the supply of rain is dependent; at the other there is small-scale evaporation from plant leaves and other organisms, of importance in micro-climatology. Between the extremes is the broad range of phenomena upon which the return of the rain to the atmosphere depends (1), phenomena of equal interest to the water engineer, the agriculturist and the pedologist. In agriculture, the transpiration of growing crops provides the main evaporation problem, but there is also evaporation from bare soil, regarded favourably when it dries out the land to permit cultivation operations, but too often regarded unfavourably when it is thought to be robbing nearby plants of moisture.

During the past few years the Physics Department has intensified the field studies in evaporation which had their foundation in the work of Dr. Keen over 25 years ago. Experiments were done in cylinders, uncropped, and a study of the retreat of the water table in various soil types, initially saturated, showed that even in the severe drought of 1921 there was little or no water movement from a water table lying at 3 or 4 ft. below the surface of Rothamsted clay soil, and for Woburn sand the limiting depth was about 14 in. (2). These experiments did not show how much water had evaporated from the soil, but, for the local soil, the drain gauges installed by Lawes and Gilbert in 1870 have provided records from which information about amounts and seasonal variation of evaporation from fallow soil could be obtained. The seasonal variation and its dependence on weather factors have become known partly from statistical analyses of the rainfall and drainage records (3, 4, 5), partly from physical reasoning and analysis of the automatic records available since 1925 (6, 7, 8), and partly from laboratory experiments (9). The results have shown that water movement in a soil with only a slight moisture deficit is extremely slow: as the deficit increases, the reluctance to move increases enormously. Drying conditions at the surface of bare soil, initially at field capacity, tend to set up a liquid movement from below to the surface. If the drying rate is small, as it is in winter, the flow of soil water can keep pace with it, so maintaining a steady evaporation rate very nearly equal to that from an open water surface and calculable from weather data. If the drying rate is great, the flow of soil water cannot keep pace with it, and the top layer of soil dries out even though moist soil conditions exist only a few millimetres away. This is characteristic summer behaviour in which the vaporisation takes place some few millimetres below the soil surface: the extra diffusion path thereby imposed reduces evaporation to very small amounts, and the rate ceases to have any dependence on weather factors other than rainfall. Thus, under English summer conditions, bare soil can be regarded as self-mulching, so that surface cultivation other than that required for weed killing is a redundant operation as far as moisture conservation is concerned, a conclusion that is in keeping with the Department's findings in cultivation experiments (10).

Recent work: theoretical

The work on bare soil showed the complexity of the problem, but in the later stages there emerged the possibility that an analytical treatment might be successful when the surface was saturated, for a crude aerodynamical estimate of evaporation rates from weather data had been successful in accounting for the observed order of magnitude (6). For a number of reasons it seemed best to apply this analysis to evaporation from an open water surface, and to obtain comparative figures for the ratios of evaporation bare soil/open water and turf/open water under conditions where soil moisture was non-limiting.

Sink strength

Two approaches have been made. In the first, evaporation is regarded as due to a difference in vapour pressure between the evaporating surface and the air above it, the rate of transport depending on the degree of turbulence in the air moving over the surface. Eddies sweeping down onto and across the surface will take up vapour and move away as slightly damper air masses, gradually to mix with their drier surroundings away from the surface. The theory of the process, developed elsewhere (11, 12), leads to the following (simplified) form for the evaporation rate:—

$$E = C\ (e_s - e_d)\ u^{\cdot 76} \qquad (1)$$

where E is the evaporation in unit time, C is a constant involving dimensional and weather factors, e_s and e_d are the water vapour pressures at the evaporating surface and in the air above respectively, and u is the horizontal wind velocity. As the analysis is effectively measuring the ability of the air to take up vapour, i.e. to act as a "sink" for vapour, it is convenient to refer to estimates based on this equation as "sink strength" estimates.

Energy balance

The second approach has been more purely physical. Evaporation is an energy change, and by treating the problem as an example of conservation of energy one might be able to draw up an energy balance sheet leaving evaporation as the only unknown. Little used for land surfaces, as the balance sheet was drawn up it was found to have been extensively used in oceanography (13). During the day, sun and sky light provide a certain measurable amount of energy, of which a small part is reflected and a negligible part used in photosynthesis. Throughout day and night an exchange of long-wave energy takes place between the earth and the water vapour of the atmosphere, partly intercepted by clouds. Precise formulation of this long wave exchange has not yet been achieved (11), but, with this limitation, it is possible to write down an expression for the heat budget (H) of the test surface as a function of incoming sun and sky radiation, mean air temperature, water vapour content of the air and cloudiness. This heat, H, is used up in evaporation, E, in warming the air, K, in warming the evaporating material, S, and in warming the surround of the material, C. Under certain conditions S and C can be ignored: an approximate expression for the ratio of K/E is available (14), and as this ratio is rarely very great it is possible to deduce E from H.

Recent work: experimental

Experiments to test these two approaches were begun in 1944 using the twelve cylinders which Dr. Keen had set up in 1924 round a pit in the meteorological enclosure. Five had been filled with Woburn soil and in 20 years had settled to a near natural state. Each of these five was joined to an empty cylinder at the bottom, so making a set of five U-tubes. Waterproof covers were provided for the empty cylinders, and on two of the soil cylinders turf was laid in the spring of 1944. One of the remaining empty pair was filled to the brim and used as an open water surface. Water was run into the empty arms of the U-tubes until they were brimful and water was standing on the soil surfaces: it was then run out until the water levels had reached pre-determined depths. These were 16 in. below bare and turfed surfaces, 10 in. below bare and turfed surfaces and 5 in. below the remaining bare surface. From the daily measured movements of the water table it was possible to estimate evaporation and transpiration, and contemporary records were taken of surface, air and dew-point temperatures, wind speed, solar radiation, and cloudiness.

Results: open water

The results have not confirmed the expectation based on the sink strength formula. It has been found that the daily evaporation rate from open water is governed by:—

$$E = 0{\cdot}35(1 + 9{\cdot}8 \times 10^{-3} u_2)(e_s - e_d) \text{ mm./day} \qquad (2)$$

where u_2 is the wind velocity in miles/day, and e_s and e_d are in millimetres of mercury. This result, which differs insignificantly from that obtained in a very comprehensive American investigation (15), differs from the formal analysis on the fundamental issue of the value of the evaporation rate at zero wind velocity. The overall mean value of observed evaporation is about two-thirds of the value that would be obtained from eq. 1 for an average wind speed.

The energy balance has been successful for periods of several days in length and has often been successful for single days. A comparison of the two approaches is given in the table below. This gives the run-of-the-wind, the value of H and the observed open water evaporation for a few days in 1945, with two estimates of evaporation alongside. The first of these has been obtained from the energy balance: the second has been obtained from eq. 2, i.e. from a fitted equation.

Observed and Estimated Evaporation: Open Water

Date 1945	u_2 m.p.d.	H (mm./day)	Evaporation (mm./day) Estimated Energy Balance	Estimated Sink Strength	Observed
June					
11	149	3·64	2·6	2·4	2·3
22	92	5·58	5·4	4·2	4·7
July					
1	197	5·01	4·3	4·7	3·2
12	50	5·80	5·0	3·1	3·6
23	128	5·76	4·7	5·7	4·8
Aug.					
3	67	4·11	3·6	4·3	3·6
17	122	3·76	4·0	2·8	2·8
26	63	3·90	3·4	3·4	3·6
Sept.					
8	128	1·53	1·3	1·4	1·8
14	133	1·36	1·4	0·9	1·1
27	146	1·63	2·0	2·3	1·7

Over extended periods the agreements are better, and applications to other data have shown that the residual empirical elements in both approaches are not purely local in their significance.

Results: bare soil

Results for bare soil have been in keeping with those of earlier work. With the water table at 5 in. below the surface the soil remained moist at all times, and the evaporation rate was about 90 per cent. of that from the open water surface in all seasons. At the next depth (10 in.) the behaviour was much the same except in extended periods of hot weather, when slight surface drying occurred, increasing in area during the day and partially recovering during the night. An appreciable decrease in evaporation rate occurred under these conditions. The transition was complete at 16 in. depth. Within two days of rain the surface dried and evaporation fell to negligible amounts: indeed, it was so slight that it was possible to detect movements of the water table due to other physical causes. It is apparent that between 10 and 16 in. under this sandy soil there is a limiting depth from below which upward movement of soil water cannot take place, a result found previously in another way by Dr. Keen.

Results: turf

In 1945 the water table held at 10 in. under turf was lowered to 24 in., so that, over the two years, data are available for water tables at 10, 16 and 24 in. There were no great differences in behaviour, the transpirations and crop yields being very nearly independent of depth of water table. Over a whole year the transpiration from the well watered turf was about three-quarters of the open water evaporation, with a summer maximum of four-fifths and a winter minimum of three-fifths. The crop used only about one half per cent. of incoming short wave energy for building up plant material. During 1946 a third turf surface was used, plentifully fertilized. Summer transpiration from the three surfaces was the same for all, but the newer turf gave a crop yield of more than double that from either of the older surfaces, again about equal. It appears that where there is a plentiful supply of water the crop behaves rather like a piece of wet blotting paper and its consumption of water is forced at one end by sunshine, wind, humidity and temperature: under drier conditions it may be restricted at the other by the inability of the roots to find sufficient water in the soil to keep pace with this external forcing. Although plant growth is also dependent upon weather conditions it is not dependent in the same way, and is more closely linked to nutrient supply and soil conditions.

Application of the results of this work to catchment areas has shown that annual run-off can be estimated from weather data and, in a similar way, specification of times and amounts of necessary irrigation are possible for intensively grown crops.

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