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BERICHTE UND KLEINE MITTEILUNGEN

ON THE STUDY OF EVAPOTRANSPIRATION AND WATER BALANCE[1])

With 2 figures

JEN-HU CHANG

Studies of regional climatology can be pursued along different lines. The dynamic and synoptic climatologist emphasizes general circulation, type of flow, air mass, perturbation, and other advective features. The micro-climatologist, on the other hand, is concerned with flux of heat, momentum, and water vapor at or near the ground surface. The dynamic approach elucidates the genesis of climate on a regional or continental scale, while the micro-climatological analysis brings out local variations shaped by the interaction between the atmosphere and the terrain. WALLEN has suggested that the two approaches be combined in a climatic classification: to recognize the major types in terms of general circulation and to delineate the subtypes on the basis of energy and moisture conditions[2]). Although it is questionable that WALLEN's scheme is rational or feasible, he realizes that the dynamic approach alone cannot satisfy the need of geographers. The study of energy budget and water balance has applications to a wide range of problems, such as the ecology of the plant community, agricultural planning, flood control, water resources management and the like.

American geographers, attracted by the rapid development of dynamic meteorology in recent years, have devoted little effort to the study of energy budget and water balance. This is evident when one compares American geography: inventory and prospect[3]) with Soviet geography: accomplishment and tasks[4]). Much of the microclimatological research in the United States has been left to the soil scientist, agronomist, hydrologist, civil engineer, and others, whose works are widely scattered and not apprehended by most geographers. Many of the microclimatological investigations by soil and plant scientists are, however, concerned with a small field for a short period of time. Their methods and results are not applicable to regional analysis unless skill is developed to generalize for a large area the observations of a point. The purposes of this paper are to review the progress in the study of evapotranspiration and water balance, to single out the methods that can be used for large-scale regionalization, and to outline the areas where further research is needed.

Definition of evapotranspiration

Evapotranspiration is the combined evaporation from all surfaces and transpiration from the plants. Except for the omission of a negligible amount of water used in the metabolic activities, evapotranspiration is the same as the "consumptive use" of plants. Evapotranspiration is a primary physical process in the ground-air interface, its intensity determining, in part, the temperature and moisture content of the air and the soil. It would be wrong to consider it a derived or secondary quantity.

As the rate of evapotranspiration from a partially wet surface is greatly affected by the nature of the ground, it is convenient first to consider the case when water supply is unlimited. This leads to the concept of potential evapotranspiration, which PENMAN defines as "the amount of water transpired in unit time by a short green crop, completely shading the ground, of uniform height and never short of water[5])." This definition, though generally accepted, suffers from a lack of precision in at least two counts. First, the "short green crop" is not specified. PENMAN argues

[1]) Published with the approval of the Director as Paper No. 46 in the Journal Series of the Experiment Station, Hawaiian Sugar Planters' Association, Honolulu, Hawaii. Acknowledgment is due Drs. J. B. LEIGHLY, R. A. BRYSON, H. E. LANDSBERG and P. C. EKERN for their criticisms.

[2]) C. C. WALLÉN, "Climatology and Hydrometeorology with Special Regard to the Arid Lands," in: Problems of the Arid Zone, UNESCO (1962), pp. 53—81.

[3]) P. E. JAMES and C. F. JONES, Eds., American Geography, Inventory and Prospect (Syracuse Univerity Press, 1954).

[4]) I. P. GERASMOV, Eds. Soviet Geography: Accomplishments and Tasks, translated by L. ECKER (American Geogr. Society, 1962).

[5]) H. E. PENMAN, "Evaporation: an Introductory Survey," Netherlands Journal of Agricultural Science, Vol. 4 (1956), pp. 9—29.

that when the cover is complete, the potential evapotranspiration is determined primarily by weather and not affected by the plant species provided that they have the same albedo. This is probably true for the crops commonly used in evapotranspiration experiments; however, some plants, such as pineapple in the tropics and lichen in the arctic, do have a very different water requirement from conventional crops. Therefore, the potential evapotranspiration should be defined as the water needs by lawn grass or some other specific vegetation.

The second and more serious flaw lies in the fact that PENMAN's definition does not spell out the size of the field and the conditions in the surrounding areas. In other words, no provision is made for the effect of advected energy. In a humid climate, where evaporation usually takes place in what PENMAN calls the "mid-ocean" environment [6]), advected energy is not a serious problem. In an arid or semi-arid climate, however, the existence of large advection of energy renders the concept of potential evapotranspiration as defined above inexact and unrealistic. For, if potential evapotranspiration requires by definition an extended evoporating surface upwind or the absence of any advected energy, then the climate is no longer arid.

Recently, PRUITT coined the term "potential maximum evapotranspiration" to designate the situation when advected energy is present [7]). This would certainly remove a confusion. Thus, one should not expect an empirical formula for potential evapotranspiration derived in the humid climate to be adequate in estimating the potential maximum evapotranspiration in an arid area. AZIZ, for instance, has found it necessary to add an advective term to the PENMAN equation in order to apply it to the arid West [8]). The disturbing problem of advected energy will be discussed fully in a later section.

Methods of Determining potential Evapotranspiration

Method of determining or estimating potential evapotranspiration fall into five general categories: (1) Direct measurement by lysimeters, (2) the aerodynamic approach based on the physics of vapor transfer process, (3) the energy budget approach, (4) empirical formulae using one or more common climatic factors, and (5) the use of evaporimeters. Some of the methods are primarily research tools for the better understanding of the physical process; others may be called "operational" in the sense that they can be applied to a large area for actual operation of regional planning.

The "operational" methods use either inexpensive field instruments or readily available mean climatic data. Since the use of mean monthly or daily values must depend upon a crude correlation between instantaneous and mean values, the empirical formulae cannot be as accurate as the elaborate "research" methods. TANNER maintains that for day-to-day operation, agriculturists can tolerate an error of ten per cent in estimating daily evaporation [9]). Likewise, for the purpose of comparative climatology on a continental scale or for regional analysis on a long-term basis, geographers can use to advantage any method that provides monthly estimates within a ten per cent error. Although geographers rely largely on "operational" methods for regionalization, the "research" methods could serve as a check, in addition to providing accurate records for a limited number of stations.

Lysimeter

The lysimeter, particularly the weighing type, is the most direct and accurate instrument for the determination of evapotranspiration. A recent installation at Tempe, Arizona, for example, weighs a 3,000 kg mass to an accuracy of 10 g or a water-depth equivalent of 0.01 mm [10]). The weighing lysimeter is capable of measuring evapotranspiration for a period as short as ten minutes. The large weighing lysimeters at Tempe, Arizona, Davis, California, and Coshocton, Ohio certainly should be used as "reference" stations in any study of water balance in the United States.

Drainage lysimeters operate on the principle that evapotranspiration can be determined if the amounts of rainfall, runoff, and percolation in a plant-soil system are known. Since percolation is a slow process, the drainage lysimeter is accurate only for a period of three days or longer, a time interval adequate for most climatological investigations.

The high cost of installation and maintenance precludes the use of the lysimeter as a routine meteorological instrument. Most of the lysimeters are used by plant and soil scientists for the study of a specific problem. In their exhaustive survey of lysimetry, KOHNKE, DREIBELBIS, and DAVIDSON counted a total of nearly 150 lysimeters throughout the world prior to 1940 [11]). The number of lysimeters has since multiplied. This mass of data has rarely been used by climatologists, partly because the information is widely scattered and partly because of its lack of homogeneity. The border effect, caused by difference in exposure and cultural treatment inside and outside the lysimeter, is often a serious problem. Nevertheless, much valuable information can be salvaged if an attempt is made to assemble all the records and adjust them to a comparable basis.

[6]) Ibid.

[7]) W. O. PRUITT, Correlation of Climatological Data with Water Requirement of Crops (Department of Irrigation, University of California, 1960), p. 18.

[8]) M. A. AZIZ, "The Influence of Advective Energy on Evapotranspiration," Utah State University M. S. thesis, 1962.

[9]) C. B. TANNER, "A simple Aero-heat Budget Method for Determining Daily Evapotranspiration," Transactions, 7th International Congress of Soil Science, Madison (1960), pp. 203—209.

[10]) C. H. M. VAN BAVEL and R. J. REGINATO, "Precision Lysimetry for Direct Measurement of Evaporation Flux," International Symposium on the Methodology of Plant Eco-Physiology, Montpellier, France (1962), 17 pp.

[11]) H. KOHNKE, F. R. DREIBELBIS and J. M. DAVIDSON, A Survey and Discussion of Lysimeters and a Bibliography on Their Construction and Performance (U.S.D.A. Miscellaneous Publication, 1940), 68 pp.

Aerodynamic approach

The aerodynamic approach rests on the assumption that the upward flow of water vapor is equal to the product of the vertical gradient of vapor pressure and the rate of mixing of the air. The rate of mixing, expressed as a coefficient of diffusion, is dependent upon the rate of change with height of the wind speed. By comparing wind and vapor profiles, THORNTHWAITE and HOLZMAN[12]) derived an expression for evapotranspiration over short vegetation which was later expanded by PASQUILL[13]) for tall crops. The Pasquill equation reads:

$$E = \frac{\varrho\, k^2 (u_2 - u_1)\, q_1 - q_2)}{\left(\dfrac{(\ln z_2 - d)^2}{z_1 - d}\right)}$$

Where E, ϱ, and k are the rate of evaporation, the air density and von Karman's constant respectively; u_1, u_2, q_1, and q_2 are the wind speeds and specific humidities at the height z_1 and z_2, and d the zero plane displacement.

This equation depends for its validity on the propositions: (1) that in the normally turbulent atmophere near the ground the eddy diffusivities for momentum and water vapor are identical and (2) that the wind profile near the ground satisfies the equation:

$$u = \frac{1}{k} \sqrt{\frac{\lambda}{\rho}}\ \frac{\ln (z - d)}{z_0}$$

where u is the wind velocity at the height z; λ, the shearing stress; and z_0, the roughness parameter.

These two propositions are valid only under the rare occasion of neutral stability. Under stable conditions when evaporation is great, eddy diffusivity for vapor, measured at a height of 75 cm, could be up to four times as great as eddy diffusivity for momentum[14]). Furthermore, the ratio between eddy diffusivities for vapor and momentum is not constant with height. VAN BAVEL and FRITSCHEN have cautioned that the vapor flux at some height above the ground is simply not equal to the vapor flux at the surface[15]).

To describe the wind profile under conditions other than neutral stability, DEACON has found it necessary to include in the equation a stability index of the Richardson number, which is difficult to evaluate[16]). Theoretically, the roughness parameter indicates the height above the ground at which the mean wind is zero, while zero plane displacement is approximately the depht of the layer of air trapped among the plants or the virtual sink for momentum. Both z_0 and d have profound micrometeorological significance, a point to be discussed later. It needs to be emphasized here that z_0 and d are extremely difficult to determine because they vary with wind speed in a complicated manner[17]). INOUE has observed that for a rice crop of 90 cm height the value of d varies from 35 to 90 cm and z_0 from 7 to 18 cm for wind speed up to 10 m/sec at the 150 cm height[18]). In this connection, it may be argued that maps of aerodynamic roughness which THORNTHWAITE urges geographers to construct are of little value[19]). The roughness map can be translated fairly accurately from a physiognomic vegetation map.

It is clear that the aerodynamic approach in its present form is fraught with theoretical difficulties. Extensive tests of the method over Lake Hefner, the surface of which is smoother than that of vegetation, have not been encouraging[20]).

Realizing the limitations of the Thornthwaite-Holzman type of approach, SWINBANK[21]) was the first to attempt direct measurement by the so-called eddy correlation technique. It can readily be shown that the eddy flux of water vapor is proportionate to the time covariance of the vertical eddy velocity and specific humidity perturbation. The difficulty lies in the design of instruments, particularly the sensing elements and the automatic data computer. Considerable progress has been made by the group of scientists at C.S.I.R.O. in Australia[22]); when their instrument is perfected for field use, it will undoubtedly be the ideal method.

The Bowen ratio

Evapotranspiration is a process of turbulent transfer as well as of energy transformation. The part of solar energy retained by the ground is called net radiation, which is disposed of mainly in three ways: Heat flux to the soil, heat flux to the air, and evatranspiration. Since the net radiation and the heat flux to the soil can be measured by instruments, it remains only to partition the energy used in evapo-

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[12]) C. W. THORNTHWAITE and B. HOLZMAN, "The Determination of Evaporation from Land and Water Surface," Monthly Weather Review, Vol. 67 (1939), pp. 4—11.

[13]) F. PASQUILL, "Some Further Consideration of the Measurement and Indirect Evaluation of Natural Evaporation," Quarterly Journal, Royal Meteorological Society, Vol. 76 (1950), pp. 287—301.

[14]) F. PASQUILL, "Eddy Diffusion of Water Vapor and Heat Near the Ground," Proceedings, Royal Society London, Ser. A., Vol. 198 (1949), pp. 116—140.

[15]) C. H. M. VAN BAVEL and L. J. FRITSCHEN, "Energy Balance of Bare Surfaces in an Arid Climate", International Symposium on the Methodology of Plant Eco-Physiology, Montpellier, France, (1962), 21 pp.

[16]) E. L. DEACON, "Vertical Profiles of Mean Wind in the Surface Layers of the Atmosphere", Geophysical Memoirs, No. 191, London (1953).

[17]) N. E. RIDER, "Evaporation from an Oat Field", Quarterly Journal, Royal Meteorological Society, Vol. 80 (1954), pp. 198—211.

[18]) E. INOUE, "The Environment of Plant Surface," Canberra Symposium on Environmental Control of Plant Growth, 1962.

[19]) C. W. THORNTHWAITE, "The Task Ahead," Annals, Association of American Geographers, Vol. 51 (1961), p. 351.

[20]) G. E. HARBECK, "The Lake Hefner Water-Loss Investigations," International Union of Geodesy and Geophysics. International Association of Scientific Hydrology, General Assembly of Toronto, Vol. 3 (1958), pp. 437—43.

[21]) W. C. SWINBANK, "The Measurement of Vertical Transfer of Heat and Water Vapor by Eddies in the Lower Atmosphere, with Some Results," Journal of Meteorology, Vol. 8 (1951), pp. 135—45.

[22]) A. J. DYER, "Measurements of Evaporation and Heat Transfer in the Lower Atmosphere by an Automatic Eddy-correlation Technique," Quarterly Journal, Royal Meteorological Society, Vol. 87 (1961), pp. 401—12.

transpiration and in heating the air. Bown has demonstrated that this takes place according to the following formula[23]):

$$\beta = \frac{A}{E} = 0.659\left(\frac{K_h}{K_e}\right)\frac{(T_s - T_a)}{e_s - e_a}$$

where β is the Bowen ratio; A, the heat flux to the air; K_h and K_e, eddy diffusivities for heat and vapor respectively; T_s, temperature of the surface; T_a, air temperature; e_s, vapor pressure of the surface; and e_a, vapor pressure of the air.

By assuming equality between K_h and K_e, the Bowen ratio can be solved from measurements of temperature and vapor gradients. The amount of evapotranspiration can be computed by the expression

$$E = \frac{(R_n - S)}{(1 + \beta)}$$

where R_n is net radiation and S the heat flux to the soil.

It is true that K_h and K_e are probably not identical even under neutral conditions, and vary greatly with thermal stratification due to the bouyancy effect[24]). But the energy balance method is relatively insensitivo to an incorrect assumption concerning the diffusivities and to the estimate of the Bowen ratio. TANNER has shown that the Bowen ratio approach fails only when the value of β is less than — 0.5[25]). This occurs only at sunrise, sunset and during the night when the evaporation is small.

The energy budget using the Bowen ratio is easier to operate and more accurate than the aerodynamic method in measuring the potential evapotranspiration in a humid climate. However, the evapotranspiration rate in the energy budget is rigidly limited by the net radiation and hence will underestimate the potential maximum evapotranspiration in areas of strong advection.

To determine the Bowen ratio accurately, it is necessary to take instantaneous readings. Mean daily values are misleading. The large temperature inversion and the small vapor pressure gradients during the night give undue weight to nighttime gradients as compared with the weight given daytime gradients which occur during the high energy flux periods. Thus the profile measurements for computing the Bowen ratio present problems not found in ordinary meteoroligical observations. Unless the method can be simplified or unless the results obtained in few stations generalized, the Bowen ratio approach will remain a research tool and does not lend itself to regionalization.

[23]) I. S. BOWEN, "The Ratio of Heat Losses by Conduction and by Evaporation from any Water Surface," Physical Review, Vol. 27 (1926), pp. 779—87.

[24]) C. H. B. PRIESTLEY and W. C. SWINBANK, "Vertical Transport of Heat by Turbulence in the Atomsphere," Proceedings, Royal Society London, Ser. A, Vol. 189 (1947), pp. 543—561.

[25]) C. B. TANNER, "Energy Balance Approach to Evapotranspiration from Crops," Proceedings, Soil Science Society of America, Vol. 24 (1960) pp. 1—9.

Simple energy budget

Measurements of the energy budget in Ontario[26]), North Carolina[27]), Missouri[28]), Hawaii[29]), California[30]), the Netherlands[31]), and England[32]) indicate that in the tropics and during the warm season in mid-latitudes, 80 to 90 per cent of the net radiation is consumed in evapotranspiration. The lower value of 80 to 85 per cent are probably correct because a small amount of advected energy exists even in a humid climate. Therefore, there is the prospect that whenever net radiation can ne measured or estimated, even a crude apportionment will permit the potential evapotranspiration to be estimated with moderate accuracy. Better understanding of the seasonal and spatial variations of the Bowen ratio would further improve the accuracy of the simple energy budget approach.

Direct measurements of net radiation are meager. The recent development of the so-called net radiometer is encouraging[33]); but until the use of the net radiometer becomes widespread, climatologists will rely on indirect methods. Net radiation can be estimated either by correlation with incoming radiation or by computing the difference between the incoming and the albedo and back radiation. The latter method is not accurate primarily because of the difficulty in estimating back radiation. The standard Brunt formula[34] for back radiation seriously underestimates the latter quantity during occasions of strong heating because it uses air temperature instead of the ground temperature. Calculations show that in the case of a grass surface 20° F warmer than the air, the net outgoing radiation may be 50 % more than that estimat-

[26]) W. G. GRAHAMA and K. M. KING, "Fraction of Net radiation Utilized in Evapotranspiration from a Corn Crop," Proceedings, Soil Science Society of America, Vol. 25 (1961), pp. 158—160.

[27]) D. G. HARRIS and C. H. M. VAN BAVEL, "A Comparison of Measured and Computed Evapotranspiration from Bermudagrass and Sweet Corn," Agronomy Abstracts (1958), p. 37.

[28]) J. F. GERBER and W. L. DECKER, A Comparison of Evapotranspiration as Estimated by the Heat Budget and Measured by the Water Balance from a Corn Field, University of Missouri Final Report USWB Contract Cwb-956, 1960.

[29]) JEN-HU CHANG, "Microclimate of Sugar Cane," Hawaiian Planters' Record, Vol. 56 (1961), pp. 195—225.

[30]) M. H. HALSTEAD, The Flux of Momentum, Heat, and Water Vapor in Microclimatology, Laboratory of Climatology Publication, Vol. 7, No. 2 (1954).

[31]) D. W. SCHOLTE UBING, "Studies on Solar and Net Radiation and on Evapotranspiration of Grass" Meded. Landbouws. School, Wageningen, Vol. 59 (1959), pp. 1—93.

[32]) G. J. HOUSE, N. E. RIDER, and C. P. TUGWELL, "A Surface Energy-Balance Computer," Quarterly Journal, Royal Meterological Society, Vol. 86 (1960), pp. 215—31.

[33]) V. E. SOUMI, M. FRANSSILA, and N. F. ISLITZER, "An Improved Net Radiation Instrument," Journal of Meteorolgy, Vol. 12 (1954), pp. 276—82.
L. J. FRISTCHEN, "Construction and Calibration of the Thermo-transducer Type Net Radiometer," Bulletin, American Meteorological Society, Vol. 41 (1960), pp. 180—183.

[34]) D. BRUNT, "Notes on Radiation in the Atmosphere: 1," Quarterly Journal, Royal Meteorolgical Society, Vol. 58 (1932), pp. 389—418.

ed from the Brunt formula [35]). The formula is accurate only to within 15 to 20 per cent for estimates over long period of time [36]).

For any locality and during any season of the year a good relationship exists between the daily incoming and net radiation, particularly if clear and cloudy days are separated, Published records in Hawaii [37]), California [38]), Iowa [39]), the Netherlands [40]), and England [41] indicate that net radiation is about two-thirds of the incoming in the tropics and during the summer in mid-latitudes. In higher latitudes the fraction of energy retained by the ground is, however, much reduced due to the higher albedo. ASLYNG in particular reported measured net radiation for Copenhagen (55° 40′ N) a 0.44 fraction of sunlight for the summer months from April to September [42]). The net radiation is a very conservative element; a few representative readings for a short period would permit the relationship between net and incoming radiation to be determined. Such studies should be given high priority.

Whatever the methods of estimating net radiation may be, accurate maps of solar radiation are a prerequisite for the simple energy budget approach. The radiation maps constructed by BUDYKO [43]) and BLACK [44]) are out of date. Both of them used fewer than 200 stations throughout the world, and BLACK could find only one station in Asia. There are actually nearly one hundred stations in China [45]), Japan [46]) and India [47]), and detailed radiation maps have also appeared in other countries [48]). With the vast amount of additional information obtained during the International Geophysical Year, a revised map should soon be constructed.

Empirical Formulae

Empirical relationships relating potential evapotranspiration to meteorological variables have been developed by THORNTHWAITE [49]), BLANEY and CRIDDLE [50]), TURC [51]), MAKKINK [52]), PENMAN [53]) and others. The THORNTHWAITE formula is best known among geographers, primarily because of its climatic classification. The limitation of the THORNTHWAITE type of formula using only air temperature has been discussed elsewhere [54]). It needs only to be reiterated that air temperature represents only a small part of the energy exchange. The temperature methods work in some areas only because temperature and radiation are often highly correlated [55]).

Experimental evidence so far lends the most support to the PENMAN formula as the best empirical method. PENMAN combined the energy budget and the aerodynamic approaches, and further simplified the equation in order to eliminate the need for difficult profile measurements. The final equation expresses evaporation as a function of temperature, radiation, wind and humidity. The Penman formula contains an energy term and an aerodynamic term; the latter is much smaller than the former but shows greater variation over small distance [56]). Inasmuch as the aero-

[35]) E. L. DEACON, C. H. B. PRIESTLEY, and W. C. SWINBANK, "Evaporation and the Water Balance," in: Climatology, UNESCO (1958), p. 14.

[36]) E. R. ANDERSON, "Energy Budget Studies," in: Water Loss Investigations. Lake Hefner Studies Technical Report, U. S. Geological Survey Circular, No. 29 (1952), pp. 71—118.

[37]) JEN-HU CHANG, op. cit.

[38]) W. O. PRUITT and D. E. ANGUS, Comparison of Evapotranspiration with Solar and Net Radiation and Evaporation from Water Surface. University of California, Davis (1961), pp. 74—107.

[39]) R. H. SHAW, "A Comparison of Solar Radiation and Net Radiation," Bulletin, American Meteorological Society, Vol. 37 (1956), p. 205.

[40]) H. J. DE BOER, Enkele Metingen van de Totale Straligsbalans en Zijn Vier Componenten op. 1.60 m Hoogte Vocen een Grasmat te De Bilt. Koninklijk Nederlands Meteorologisch Institute 46 (R III—229), 1959.

[41]) J. L. MONTEITH, and G. SZEICZ, "The Radiation Balance of Bare Soil and Vegetation," Quarterly Journal, Royal Meteorological Society, Vol. 87 (1961), p. 159.

[42]) H. C. ASLYNG, and B. F. NIELSEN, "The Radiation Balance at Copenhagen," Archiv for Meteorologie, Geophysik und Bioklimatologie B, Vol. 10 (1960), p. 23.

[43]) M. I. BUDYKO, The Heat Balance of the Earth's Surface, U. S. Weather Bureau translation (1958), 259 pp.

[44]) J. N. BLACK, "The Distribution of Solar Radiation over the Earth's Surface," in: Wind and Solar Energy, UNESCO (1956), pp. 138—140.

[45]) WEN-JUN XIAO, The Distribution of Total Annual and Seasonal Insolation in China," Acta Meteorologica Sinica, Vol. 30 (1959), pp. 186—190.

[46]) K. SEKIHARA, and M. KANO, On the Distribution and Variation of Solar Radiation in Japan," Papers in Meteorology and Geophysics, Vol. 8 (1957), pp. 144—49.

[47]) A. MANI, M. S. SWAMINATHAN, and S. P. VENKITESHWARAN, "Distribution of Sunshine and Solar Radiation over the Indian Peninsula," Indian Journal of Meteorology and Geophysics, Vol. 13 (1962), pp. 195—212.

[48]) A. J. DRUMMOND and E. VOWINEKEL, "The Distribution of Solar Radiation Throughout Southern Africa," Journal of Meteorology, Vol. 14 (1957), pp. 343—53. C. L. MATEER, "A Preliminary Estimate of the Average Insolation in Canada," Canadian Journal of Agricultural Science, Vol. 35 (1955), pp. 579—94.

[49]) C. W. THORNTHWAITE, "An Approach Toward a Rational Classification of Climate," Geographical Review, Vol. 38 (1948), pp. 55—94.

[50]) H. F. BLANEY and W. D. CRIDDLE, Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data, U. S. Soil Conservation Service, Technical Paker (1950), 96 pp.

[51] L. TURC, "Le Bilan d'eau des sols. Relations entre les precipitations, l'evaporation et l'ecoulement," Annales Agronomiques, Vol. 5 (1954), p. 491.

[52]) G. F. MAKKINK, "Ekzameno de la Formulo de PENMAN," Netherlands Journal of Agricultural Science, Vol. 5 (1957), p. 290.

[53]) H. E. PENMAN, "Natural Evaporation from Open Water, Bare Soil, and Grass," Proceedings, Royal Society, Ser. A, Vol. 193 (1948), pp. 120—145.

[54]) JEN-HU CHANG, "An Evaluation of the 1948 THORNTHWAITE Classification," Annals, Association of American Geographers, Vol. 49 (1959), pp. 24—30.

[55]) W. L. PELTON, K. M. KING and C. B. TANNER, "An Evaluation of the THORNTHWAITE and Mean Temperature Methods for Determining Potential Evapotranspiration," Agronomy Journal, Vol. 52 (1960), pp. 387—395.

[56]) G. STANHILL, "The Use of the Piche Evaporimeter in the Calculation of Evaporation," Quarterly Journal, Royal Meteorological Society, Vol. 88 (1962), pp. 80—82.

dynamic term is a small one, the PENMAN equation is only slightly better than the simple energy budget approach, but requires additional wind, humidity and temperature data.

When radiation is not directly measured, PENMAN uses crude estimates from cloudiness data; thus, the PENMAN method is very much dependent upon the accuracy of the radiation records. But even with accurate radiation data, the formula does not apply to periods of less than five days. In comparison with a lysimeter, BUSINGER obtained daily PENMAN estimates varying by as much as 25 per cent, whereas the total over 25 days was estimated to within one per cent [57]).

Inasmuch as the PENMAN formula estimates only potential evapotranspiration, attempts have been made to apply a factor or to adjust the equation so that it can be used to estimate the potential maximum evapotranspiration for a particular area. The adjustment undoubtedly serves a specific purpose, but in no way improves the formula as such. In this connection, it needs to be pointed out that no empirical formula can be expected to estimate potential maximum evapotranspiration from the coast right to the heart of a continent.

Evaporimeters

Atmometers and evaporation pans have been extensively employed by hydrologists and agronomists in obtaining estimates of evapotranspiration. The evaporation pan is better than the atmometer, because the latter is unduly sensitively to the wind [58]). Because color, size, and material all affect the evaporation rate from a pan, the World Meteorological Organization has adopted the U.S. Weather Bureau Class A pan as the interim international standard for the International Geophysical Year. A working group under the Commission for Instruments and Method of Observation is examining the question of an international standard, including the possibility of using an insulated pan [59]). It is true that a physicist can quickly find faults even with a standard pan in its heat storage, rim effect, and the differences in albedo and roughness between water and land surfaces. But experimental evidence shows that such theoretical shortcomings are of only minor consequence. Comparisons of various methods with lysimeter readings in Hawaii [60]), Israel [61]), Japan [62]), and California [63]) indicate 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. The data from Davis, California, in particular, show that pan evaporation and evapotranspiration are highly correlated even on a daily basis. Fully realizing the value of the evaporation pan, the group of experts attending the UNESCO Canberra symposium on climatology recommended its wide use throughout the world [64]).

The extensive evaporation pan records in the United States have been analyzed by KOHLER, NORDENSON and FOX [65]). They constructed maps of lake evaporation based on the pan data. With the knowledge gained from lysimeter for various crops, maps of lake evaporation can in turn be converted into maps of potential maximum evapotranspiration.

In other parts of the world, measurement of pan evaporation often lack homogeneity. The proper exposure of the pan in an arid climate is a particularly important factor to be considered.

Advected energy

Advected energy resolves itself into the "clothesline effect" and the "oasis effect". When warm air blows through a small plot with little or no guard area, a very severe horizontal heat transfer occurs, which TANNER calls the "clothesline effect" [66]). Inside a large field the vertical energy transfer from the air above to the crop is called the "oasis effect" by Lemon et al [67]).

The clothesline effect cannot be tolerated in either agronomic or climatological investigations. It represents the experimental bias due to the small size of the field. Both THORNTHWAITE [68]) and STANHILL [69]) consider an upwind guard ring of 300 m. distance necessary to minimize the clothesline effect. At the edge of the border the evaporation rate could increase by as much as 40 per cent due to the clothesline effect. Records of evaporation pan and lysimeter that do not meet this requirement must be adjusted. In reducing the evaporimeter data, SUTTON's rule that the total evaporation from a circular wet surface in completely dry surrounding varies with the 1.88th power of the radius is a useful approximate guide [70]).

[57]) J. A. BUSINGER, "Some Remarks on PENMANs Equation for the Evapotranspiration," Netherlands Journal of Agricultural Sciences, Vol. 4 (1956), pp. 77—80.

[58]) E. I. MUKAMMAL and J. P. BRUCE, Evaporation Measurements of Pan and Atmometer, Meteorological Branch, CIR.-300, Tec.-315. 1960.

[59]) T. J. NORDENSON and D. R. BAKER "Comparative Evaluation of Evaporation Instruments," Journal of Geophysical Research, Vol. 67 (1962), pp. 671—79.

[60]) JEN-HU CHANG, 1961, op. cit.

[61]) G. STANHILL, "A Comparison of Methods of Calculating Potential Evapotranspiration from Climatic Data," Israel Journal of Agricultural Research, Vol. 11 (1961), pp. 159—171.

[62]) S. SUZUKI and H. FUKUDA, "A Method of Calculating Potential Evapotranspiration from Pan Evaporation Data," Journal of Agricultural Meteorology, Vol. 13 (1958), pp. 81—85.

[63]) PRUITT, op. cit.

[64]) UNESCO, *Climatology and Microclimatology*, Canberra Symposium, 1958, p. 93.

[65]) M. A. KOHLER, T. J. NORDENSON and W. E. FOX, Evaporation from Pans and Lakes, U. S. Weather Bureau Research Paper No. 38, 1955.

[66]) C. B. TANNER, "Factors Affecting Evaporation from Plants and Soils," Journal of Soil and Water Conservation, Vol. 12 (1957), pp. 221—227.

[67]) E. R. LEMON, A. H. GLASER, and L. E. SATTERWHITE, "Some Aspects of the Relationship of Soil, Plant, and Meteorological Factors to Evaporationspiration," Procedings, Soil Science Society of America, Vol. 12 (1957), pp. 464—68.

[68]) C. W. THORNTHWAITE, "A Re-examination of the concept and Measurement of Potential Evapotranspiration," Laboratory of Climatology Publication, Vol. 7 (1954), pp. 200—209.

[69]) STANHILL, 1961, op. cit.

[70]) O. G. SUTTON, "Wind Structure and Evaporation in a Turbulent Atmosphere," Proceedings, Royal Society, London, Ser. A. Vol. 146 (1934) pp. 701—722.

The oasis effect must be reckoned with as a climatic characteristic, since it is measurable many miles into an irrigated field. GAL'TSOV, for instance, has observed the oasis effect in the center of large irrigated region in Kazakhstan [71]). This effect accounts for the excess of actual evapotranspiration over the potential as prescribed by the net radiation. In extreme cases the advected energy may approach net radiation.

There is no simple way to evaluate the advected energy. The oasis effect depends upon the size of the field as well as upon the difference in temperature an humidity between the field and its surroundings. Any attempt to assess the advected energy quantitatively requires a combination of both the turbulent transfer and the energy budget approach. Such a study has been undertaken by DE VRIES, who developed a theoretical model based on the assumption of homogeneous surface and constant diffusivities [72]). His approach is, however, too complicated for general use. The apparatus for the eddy correlation technique is also useful in studying the advective influence. Climatologists will have to wait until these methods are perfected before they can reconcile the difference between potential maximum evapotranspiration with confidence.

Vegetation effect

Meteorologists tend to dismiss the vegetational effect. They claim that the rate of potential evapotranspiration is dictated by the weather conditions. That this is indeed not true for all crops has been demonstrated by plant scientists. From the standpoint of water use, crops may be loosely divided into two groups: conventional and non-conventional. The water use of a conventional crop by and large meets the specification set by meteorologists. On the other hand, the potential evapotranspiration of a non-conventional crop is greatly influenced by its physiology. Most of the field crops, however, belong to the conventional group.

PENMAN and SCHOFIELD [73]) gave three reasons why the consumptive use of a short crop of the conventional group is less than open water evaporation: (1) the higher albedo of the vegetation, (2) closure of stomata at night and (3) diffusion impedence of the stomata. NEUMANN argued from the standpoint of turbulence theory that the water use of a short crop is approximately 75 percent of the open water evaporation, a figure in close agreement with measurements for short grass [74]).

In general, the consumptive use of a conventional crop increase with its height. Thus the ratio between evapotranspiration and evaporation from the Class A pan increases from 0.75 for short grass to 0.87 for corn [75]) and to 1.0 for sugar cane [76]). The high water use by a tall vegetation is accounted for by the increased roughness (z_0) and zero plane displacement (d) at a given wind speed. Apart from the fact that increased z_0 facilitates the removal of water vapor by virtue of the steep wind speed gradient near the ground, the energy budget of a field is also altered. Other things being equal, the maximum noon temperature is lower and the minimum night temperature is higher, as values of z_0 and d increase [77]). The lower maximum daytime temperature necessarily reduces the outgoing radiation and increases the net radiation [78]). DECKER, for instance, has found that the net radiation over bluegrass is 12 per cent less than over corn, and 8 per cent less than over alfalfa [79]). In Hawaii both sugar cane and pineapple have a net radiation two-thirds of the incoming, yet the albedo of pineapple is only 5 per cent as against 16 per cent for sugar cane. The tall vegetation of sugar cane must have a lower back radiation.

For the non-conventional crops the consumptive use is largely determined by its physiology, particularly the behavior of the stomata. Rice, with an evapotranspiration and pan evaporation ratio of 1.2 [80]) and pineapple, with a ration of 0.33, are good examples. Lichen and moss in the arctic are also very conservative in their water use.

For most of the annual crops the evapotranspiration reaches the potential rate only for a short period when the plant is actively growing and the cover is complete. In both the early and late growth stages water needs fall short of the potential. During the ripening period the consumptive use is slightly reduced senescence [81]). In the early stage of the crop growth the low evapotranspiration rate is due to the existence of a large portion of bare ground. Theoretically, if the ground is kept wet all the time evaporation from bare ground may even exceed free water evaporation [82]. In reality, irrigation cannot be applied continuously to a large area. With high radiation conditions a surface mulch of dry soil may develop within a few hours after the soil is wetted, and from then on the

[71]) A. P. GAL'TSOV, "O Klimatishekom vzaimodeiztvii oroshaemykh i neroshaemykh ploshchadei,", Akad. Nauk SSSR, Ser. Geogr., Vol. 3 (1953), pp. 11—20.

[72]) D. A. DE VRIES, "The Influence of Irrigation on the Energy Balance and the Climate Near the Ground," Journal of Meteorology, Vol. 16 (1959), pp. 256—270.

[73]) H. E. PENMAN and R. K. SCHOFIELD, "Some Physical Aspects of Assimilation and Transpiration," Symposia Society of Experimental Biology, Vol. 5 (1951), pp. 115—129.

[74]) J. NEUMANN, "On a Relationship Between Evaporation and Evapotranspiration," Bulletin, American Meteorological Society, Vol. 34 (1953), pp. 454—457.

[75]) L. J. FRITSCHEN, "Transpiration and Evapotranspiration as Related to Meteorological Factors," Iowa State University Ph. D. thesis, 1960.

[76]) JEN-HU CHANG, 1961, op. cit.

[77]) H. LETTAU, „Synthetische Klimatologie", Berichte des Deutschen Wetterdienstes Bad Kissingen, Vol. 38 (1952), p. 127.

[78]) D. W. SCHOLTE UBING, "Solar and Net Radiation, Available Energy and its Influence on Evapotranspiration from Grass," Netherlands Journal of Agricultural Science, Vol. 9 (1961), pp. 81 93.

[79]) W. L. DECKER, "Variation in the Net Exchange of Radiation from Vegetation of Different Heights," Journal of Geophysical Research, Vol. 64 (1959), pp. 1617—1619.

[80]) SUZUKI and FUKUDA, op. cit.

[81]) G. STANHILL, "The Control of Field Irrigation Practice from Measurement of Evaporation," Israel Journal of Agriculture Research, Vol. 12 (1962), pp. 51.62.

[82]) L. J. FRITSCHEN and C. H. M. VAN BAVEL, "Energy Balance Components of Evaporating Surfaces in Arid Lands," Journal of Geophysical Research, Vol. 67 (1962), pp. 5179—85.

evaporation rate drops sharply. Thus, in the early stage of the crop cycle the evapotranspiration rate is only about 40 per cent of the pan evaporation, if the field is irrigated at weekly intervals[83]). Freezing also curtails evapotranspiration. KING cites one instance in which the fraction of net radiation used in evapotranspiration dropped from 0.85 to 0.52 after freezing[84]). Caution must be exercised in estimating the water needs of crops in high latitudes.

Actual evapotranspiration

As the soil dries out, the actual evapotranspiration will, at some stage, fall below the potential rate. There is considerable controversy as to the effect of moisture tension on the depletion rate. The measurements made by VEIHMEYER and HENDRICKSON at Davis, California, show that evapotranspiration proceeds at the potential rate up to the wilting point and falls sharply thereafter[85]). THORNTHWAITE and MATHER, on the other hand, show a linear decline of evapotranspiration with increasing tension, based on the data at O'Neill, Nebraska[86]). There are still others who propose a compromise between these two extremes, PIERCES curve as presented in Figure 1 being a good example[87]).

The conflicting state of evidence is by no means due to experimental errors. Recent studies by MAKKINK and van HEEMST[88]), and by DENMEAD and SHAW[89] suggest that the depletion rate is very much dependent upon environmental conditions. The constant depletion rate reported by VEIHMEYER and HENDRICKSON hold true in a humid, cloudy climate, particularly if the soil is heavy and covered by dense vegetation. Conversely, in bare sandy soil of an arid climate, the depletion rate would decline rapidly.

In view of the changing relationship between the moisture tension and the depletion rate, climatologists should select proper curves for the major climatic regions, such as the humid tropics, arid land, taiga, and tundra, etc. The use of the wrong curve could result in sizable errors, as is demonstrated by HOLMES[90]). Ideally, the depletion curve should be checked against soil moisture readings, but even a crude adjustment could improve the computation considerably. For some parts of the world the tables prepared by THORNTHWAITE and MATHER[91]) and the nomograph by WARTENA and VELDMAN[92]) are useful references.

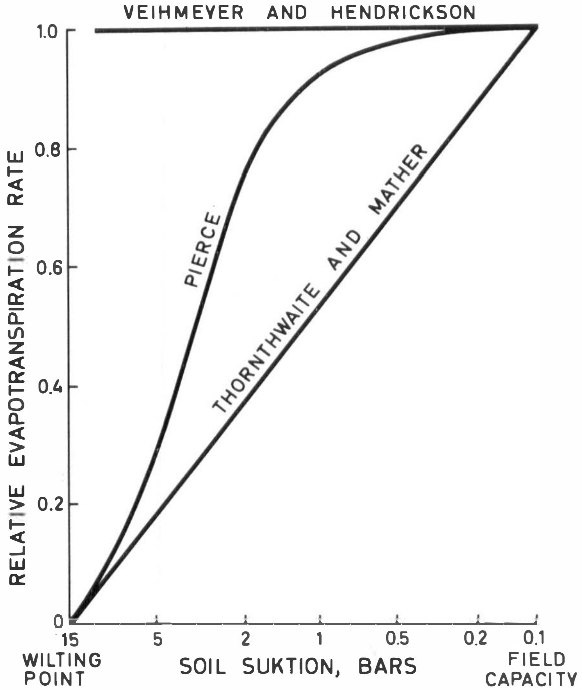

Figure 1

Water Balance

The water balance equation of the plant-soil system down to the rooting depth can be expressed as follows:

Rainfall – Evapotranspiration – Runoff – Leaching-Change in soil moisture storage.

Once the evapotranspiration is known, it remains only to determine the soil moisture storage to solve the equation. THORNTHWAITE and MATHER adopted a storage capacity of 30 cm as the average for the world[93]). This is at best crude. For many a practical problem the storage capacity must be measured with

[83]) B. D. DOSS, O. L. BENNETT, and D. A, ASHLEY, "Evapotranspiration by Irrigated Corn," Agronomy Journal, Vol. 54 (1962), pp. 497—498. JEN-HU CHANG, 1961, op. cit.

[84]) K. M. KING, "Evaporation from Land Surfaces," in: Proceedings of Hydrology Symposium No. 2, Evaporation, National Research Council of Canada, Toronto, 1961, p. 68.

[85]) F. J. VEIHMEYER, and A. H. HENDRICKSON, "Does Transpiration Decrease as the Soil Moisture Decreases?" Transactions, American Geophysical Union, Vol. 36 (1955), pp. 425—48.

[86]) C. W. THORNTHWAITE and J. R. MATHER, "The Water Budget and Its Use in Irrigation," in: U. S. Department Yearbook of Agriculture, 1955, pp. 346—58.

[87]) L. T. PIERCE, "Estimating Seasonal and Short-term Fluctuations in Evapotranspiration from Meadow Crops," Bulletin, American Meteorological Society, Vol. 39 (1958), pp. 73—78.

[88]) G. F. MAKKINK and H. D. J. VAN HEEMST, "The Actual Evapotranspiration as a Function of the P tential Evapotranspiration and the Soil Moisture Tension," Netherlands Journal of Agricultural Science, Vol. 4 (1956), pp. 67—72.

[89]) O. T. DENMEAD and R. H. SHAW, "Availability of Soil Water to Plants as Affected by Soil Moisture Content and Meteorological Conditions, Agronomy Journal, Vol. 45 (1962), pp. 385—90.

[90]) R. M. HOLMES, "Estimation of Soil Moisture Content Using Evaporation Data", in: Proceedings of Hydrology Symposium No. 2, Evaporation, National Research Council of Canada, Toronto, 1961, pp. 184—96.

[91]) C. W. THORNTHWAITE and J. R. MATHER, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance, Laboratory of Climatology Publication, Vol. 3 (1957), pp. 185—311.

[92]) L. WARTENA and E. C. VELDMAN, "Estimation of Basic Irrigation Requirements," Netherlands Journal of Agricultural Science, Vol. 9 (1961), pp. 293—298.

[93]) C. W. THORNTHWAITE and J. R. MATHER, The Water Balance, Laboratory of Climatology (1955), 104 pp.

precision. For the purpose of comparative climatology on a continental scale, it is best to adopt standard values for various major regions of the world. Routine observations of soil moisture have been carried out in agrometeorological stations in Russia and West Germany for many years. Increasing effort have been made elsewhere to measure the storage capacity following the recommendation by the World Meteorological Organization [94]). With the use of neutron scattering meters, pressure membrane apparatus, and other instruments, the problem of determining soil moisture storage capacity is no more than one of proper sampling.

In the water balance computation, runoff and leaching are lumped together as surplus. Surplus occurs whenever the rainfall exceeds the moisture storage capacity. This is only an approximation. In actuality runoff is the excess of rainfall over infiltration rather than over storage. Furthermore, the disposal of excess water in the form of leaching does not take place immediately. The process takes a day or even longer. While significant errors may incur in daily computation due to incorrect assumptions regarding runoff and leaching, they cannot be large when applied to a period of a month or longer, especially over a large area.

The difference between rainfall and surplus is a measure of the effective rainfall. The effective rainfall is much less variable than rainfall and, when computed on a daily basis, it can be accurately determined with a short period of records, say three to five years. The effective rainfall is not very sensitive to an error in the estimate of storage capacity. The maximum difference caused by using two different values of storage capacity cannot exceed the difference in storage capacity times the number of heavy rains exceeding the larger of the two. The writer has found that in most parts of Hawaii the difference in effective rainfall by assuming storage capacities of two and four inches is only about four inches a year [95]). World maps of effective rainfall are urgently needed in agricultural climatology. They can be constructed fairly accurately with the information now available.

Drought occurs whenever the soil moisture is depleted. The total amount of water deficit throughout the year is a measure of the aridity of a climate. The amount of water deficit is, however, quite sensitive to a change in moisture storage capacity.

Example of application

The solution of the water balance equation has many practical applications which have yet to be fully explored, one example being the study of the relation between climate and yield. The customary procedure of correlating yield with temperature and rainfall is so crude that it contributes little in actual operation and long-range regional planning. Only through the application of the water balance and other sophisticated concept could the effect of climate on yield be expressed in exact, quantitative terms.

Physiologically, the dry matter production of a crop is proportionate to the amount of transpiration. Following this concept, the research workers at the Experiment Station, Hawaiian Sugar Planters' Association, have derived a relation between water and sugar cane yield as presented in Figue 2 [96]). In this diagram

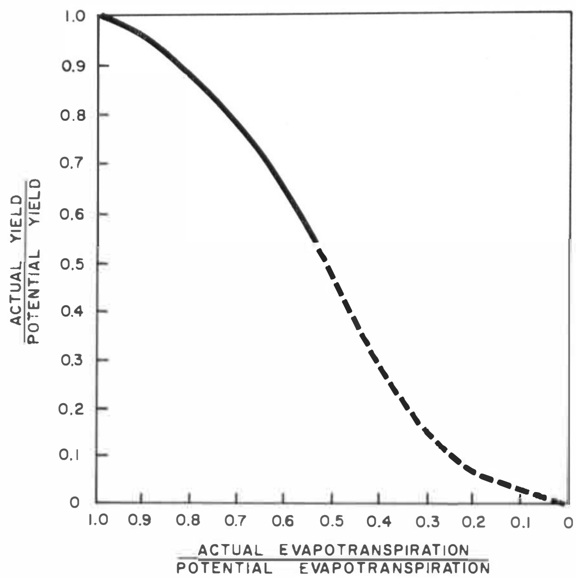

Fig. 2: Relationship between sugar cane yield and water application in Hawaii. Excessive water reduces yield.

the ratio between the actual and potential yield is expressed as a function of the ratio between actual and potential evapotranspiration. The latter quantity is a measure of the adequacy of water application. The solid portion of the curve can be expressed by the following equation:

$$\frac{\text{Actual yield}}{\text{Potential yield}} = -0.61 + 2.70X - 1.09X^2$$

$$\text{where } X = \frac{\text{Actual evapotranspiration}}{\text{Potential evapotranspiration}}$$

Since the value of X can be readily evaluated by water balance computation, the potential yield of an area, when water is not limiting, can be estimated from actual yields. The yield loss due to inadequate water application can also be assessed. The equation has been found to be accurate within seven per cent of the actual yield data.

The equation has been used as the basis for computing various alternatives of land use and water resources planning in the sugar industry in Hawaii. For the first time it has been possible to determine the most profitable land and water use pattern for a given set of condition. Whether such studies of plant and

[94]) International Meteorological Organization, Commission for Agricultural Meteorology, Eighth Session at Toronto, August 1947, Final Report, 1949, pp. 28—30.

[95]) Jen-hu Chang, "The Role of Climatology in the Hawaiian Sugar Industry: An Example of Applied Agricultural Climatology in the Tropics," to be published in the Pacific Science, July, 1963.

[96]) Jen-hu Chang, R. B. Campbell, and F. E. Robinson, "On the Relationship Between Water and Sugar Cane Yield in Hawaii," to be published in: Agronomy Journal, Sept. 1963.

yield relationship are geographical or not, they certainly open up a new horizon in regional analysis of land use and water resources management.

Conclusion

The study of evapotranspiration has been a difficult and often controversial subject in meteorology. Part of the difficulty stems from the fact that the potential evapotranspiration and potential maximum evapotranspiration are not distinguished even among the research workers in the field. For the estimation of potential evapotranspiration the PENMAN equation and the simple energy budget approach are adequate. For the determination of potential maximum evapotranspiration, the evaporation pan, when properly handled, is probably the best field instrument, although the apparatus for eddy correlation technique show great promise. In any event the various methods should be checked against lysimeter results whenever possible.

The large body of lysimeter, pan evaporation, energy budget and other data scattered throughout the world needs to be assembled and put into useful form. For those parts of the world where routine observations are scanty, sample studies of the BOWEN ratio, the relationship between net and incoming radiation, the depletion curve, and the storage capacity go a long way toward solving the water balance equation. Such sample studies do not have to be carried out for a long time, since most items in the aquation do not vary greatly from year to year. This derivation of climatic norms from a few point studies is one of the objectives of what BRYSON calls "field climatology"[97]).

The study of the water balance requires a consideration not only of meteorological facts, but also of soil and vegetation factors. The classifications by KÖPPEN and THORNTHWAITE leave much to be desired in view of recent progress in the study of evapotranspiration. When properly determined, each item in the water balance equation has a definite physical meaning. No longer should moisture conditions be characterized in vague or meaningless indices, suitable for descriptive and pedagogic purposes but invariably failing outside the classroom. If quantification has a place in human geography, all the more should it be used with precision in physical geography.

Literature

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HAUDE, W.: Die Verteilung der potentiellen Verdunstung in Ägypten. In: *Erdkunde*, Bd. XIII, H. 3 (1959).

HAUDE, W. Zur Bestimmung der Verdunstung und des Wasserhaushaltes in Trockengebieten des Vorderen Orients zwischen Nil und Euphrat. In: Wasser und Boden 1963.

97) R. A. BRYSON, oral communication.

HAUDE, W.: Zur praktischen Bestimmung der aktuellen und potentiellen Evapotranspiration. Mitt. d. Dt. Wetterdienstes Nr. 8 Bad Kissingen 1954.

ALBRECHT, F.: Die Berechnung der natürlichen Verdunstung (Evapotranspiration) der Erdoberfläche aus klimatologischen Daten. Ber. d. Dt. Wetterdienstes Bd. 83, 1962, S. 1—19.

UHLIG, S. Berechnung der Verdunstung aus klimatologischen Daten. Mitt. d. Dt. Wetterdienstes 6, 1954, 1—24.

For further reading see bibliography in:

KELLER, R. Gewässer und Wasserhaushalt des Festlandes, Berlin 1961, Leipzig 1962.

DIE SÜDLICHEN OSTERSEEN BEI IFFELDORF IN OBERBAYERN

Luftbildinterpretation einer Jungglaziallandschaft

Mit 3 Abbildungen und 1 Luftbild

JOHANN BODECHTEL

Summary: The southern Oster lakes near Iffeldorf, Upper Bavaria.

Using as example the Oster lake area, the relief of which is due to the disintegration of the Quaternary ice sheet, the paper demonstrates the applicability of geomorphological interpretation of air photographs for identifying glacial deposits. Photo-geological analysis facilitates their immediate classification. Various glacial landforms which are frequently only distinguishable on an morphological basis, such as aser, drumlins, kames and kettleholes, can thus be mapped with a degree of precision hardly attainable in field mapping.

Die photogeologische und geomorphologische Interpretation, die sich zur Deutung eines Luftbildes weitgehend an typische morphologische Erscheinungen anhängt, ist ganz besonders geeignet, in formenreichen Glaziallandschaften, wo die Mannigfaltigkeit des Kleinreliefs im Gelände das Bild leicht verwirrt, als bevorzugtes Hilfsmittel zu dienen. Neben dem größeren Überblick über die allgemeinen Zusammenhänge erlaubt die stereoskopische Betrachtung von Luftbildern auch ein detailliertes Studium der oft nur nach ihrer Ausbildung und Form einzustufenden glazialen Bildungen. Als äußerst günstig erweist sich die zwei- bis vierfache Überhöhung des Reliefs im Stereomodell. So ist es möglich, in einer Glaziallandschaft, die zwar formenreich ist, aber meist keine großen Höhenunterschiede aufweist, durch die Überhöhung auch noch kleinste Reliefunterschiede zu unterscheiden und so kleine, aber oft typische Formen übertrieben und somit klarer und eindeutiger zu erkennen.

Das hier herausgegriffene Beispiel umfaßt einen Teil des bekannten Osterseengebietes (ROTHPLETZ 1917, WASMUND 1934, ZORELL 1924, 1941) südlich des Starnberger Sees (Abb. 1). Diese Seenplatte zeigt eine typische Eiszerfall-Landschaft der Rückzugsphase der letzten Würmvereisung, die sich in diesem Gebiet vom Südufer des Starnberger Sees bis an den Alpenrand bei Kochel und Murnau erstreckt (TROLL 1938). Das Luftbild, das unter dem Stereoskop mit Hilfe der seitlich bei 60 % Überlappung anschließenden Bildern interpretiert wurde, erfaßt einen Teil des Ostersees und der Staltacher Seen am oberen Bildrand, den Fohnsee, den Sengsee und die Iffeldorfer Seen. Am rechten