U. S. DEPARTMENT OF COMMERCE
U.S. WEATHER BUREAU
Washington, D. C.
November 9, 1960

COMPUTING SOIL MOISTURE DEFICIENCIES ACCORDING TO THE KOHLER METHOD

Howard H. Engelbrecht
U. S. Weather Bureau, Friendship International Airport, Baltimore, Md.

[Manuscript received August 4, 1960]

ABSTRACT

An IBM 650 program has been developed to solve a complex empirical equation for computing potential evapotranspiration and performing soil moisture accounting in an elegant manner based on the Kohler method. Various climatological statistics produced as by-products of this program may be useful to bioclimatologists and others.

INTRODUCTION

A system for computing potential evapotranspiration and accounting for loss of moisture from soils through evapotranspiration on a daily basis has been outlined by Kohler (1957). This procedure is expected to have widespread application to river and flood forecasting, a very important problem in hydrology. The moisture deficiency values derived by this technique are used to indicate the volume of runoff to be expected from observed magnitudes of storm rainfall. The main obstacle in the development of flood forecasting schemes based on the Kohler potential evapotranspiration and soil moisture accounting is the requirement for a large amount of manual computation and bookkeeping, since forecasting relationships must be grounded on, preferably, many years of observed data. The performance of one day's accounting in connection with the preparation of day-to-day forecasts, however, can be done readily in a manual fashion. Consequently, the primary need for high speed computation is in the development of the forecasting procedures. Although graphical relations have been devised, a somewhat more rapid and economical method for deriving potential evapotranspiration and soil moisture deficiencies seemed to be highly desirable for speeding up the production or revision of river and flood forecasting procedures. This has been done through the development of IBM 650 Program HHE002 which is described briefly in this paper.

POTENTIAL EVAPOTRANSPIRATION

Basic in this problem is the computation of potential evapotranspiration by the complex equation developed by Kohler. This equation is used as an approximation to the graphical relationships which were developed through correlation (Kohler and others, 1955). Theoretically, the equation would be considered of lower accuracy than the graphical relations from which it was derived; however, for practical purposes, eliminating the chance for human errors in tracing through graphical relationships, the equation may objectively produce results of higher quality. The Kohler potential evapotranspiration equation is expressed as follows:

$$E = \frac{e^{(F-212)(0.1024-0.01066 \mathrm{Log}_e R)} - 0.0001+0.0105p^{0.88}(0.37+0.0041 \times u)}{0.015 + \dfrac{5.561 \times 10^{11} \times e^{-(9943)/(F+460)}}{(F+460)^2}} \qquad (1)$$

in which $\underline{F}$ is the average temperature in °F., $\underline{R}$ is the total solar radiation in langleys per day, $\underline{p}$ is the vapor pressure deficit in inches of mercury based on the average temperature and average dew point, and $\underline{u}$ is the total wind movement in miles per day at evaporation pan height. Additional input data required for IBM 650 Program HHE002 are precipitation in inches and total runoff in inches per day. If solar radiation data are not available, percent of possible sunshine may be substituted in the input data and by a routine in the computer program the solar radiation is estimated on the basis of the sunshine data (Hamon and others, 1954). Also, if wind data are given for any height above pan height or in terms other than total miles of wind movement per day, appropriate factors are inserted into the computer program to reduce wind data to the proper variable required for $\underline{u}$ in equation (1).

SOIL MOISTURE ACCOUNTING

Along with a computation of the potential evapotranspiration, a somewhat different concept of soil moisture reduction (evapotranspiration) is used in the Kohler method. Assuming initial conditions at field capacity, for example, soil moisture is reduced at the potential rate until, say, 2 inches of deficiency is obtained in the "upper" layer. Two inches is also the capacity for available moisture in the upper layer in this example. However, the upper layer is not necessarily assigned a capacity of 2 inches in all cases.

Any further reduction of soil moisture is based on the following relationship:

$$e_S' = (1 - D_1/S)\, e_S \qquad (2)$$

in which e_S' is the actual evapotranspiration from the "lower" layer, e_S is the potential evapotranspiration from the lower layer, D_1 is the deficiency in the lower layer on the previous day, and $\underline{S}$ is the capacity for available moisture in the lower layer or its maximum deficiency. The idea of an upper and a lower layer is explained further below.

Moisture added to the soil moisture reservoir is determined by calculating daily recharge which is the daily precipitation less the daily contribution to total runoff. Recharge is first used to replenish any deficiency in the upper layer. As soon as the upper layer is saturated, recharge reduces the deficiency of the lower layer which may reach a deficiency of, say, 10 inches. Following recharge, moisture is again lost from the upper layer at the potential rate until the selected maximum deficiency obtains, when evapotranspiration again comes from the lower layer.

The Kohler concept of soil moisture accounting overcomes some of the objections raised against the methods commonly used by other research workers. That is, after a considerable deficiency has developed and a small or moderate recharge occurs, the Kohler method allows for a more rapid and realistic reduction of the moisture which is in the "upper" layer. Some methods would have this "fresh" recharge added uniformly to the entire soil moisture storage profile and reduced at a rate dependent upon the total amoont. This procedure results in an evapotranspiration rate only slightly higher than the rate before the recharge, although we actually know that surface moisture is lost quite rapidly. With properly chosen values of <u>s</u> (the capacity for available moisture in the upper layer or its maximum deficiency) and <u>S</u> (the capacity for available moisture in the lower layer or its maximum deficiency) and with accurate values for runoff and precipitation, <u>D</u>, the lower layer deficiency, should not exceed <u>S</u> and the recharge to the lower layer should not reduce the deficiency to less than zero.

OUTPUT AND BY-PRODUCTS

Daily values of <u>d</u>, the deficiency in the upper layer, and <u>D</u> are required for flood forecasting procedures. In addition to these values certain by-products are available for other purposes in the output data of the IBM 650 program. Output data in the form of eight 10-digit words include the following statistics:

SSIIIIYYEE $M_oM_oD_aD_a$sssrrr RRR-D-D-DPPPP $e_te_te_se_se_Se_S$QQQQ MMMMmmmmTT

$D_pD_p\%_1\%_1\%_1\%_2\%_2\%_2e'_Se'_S$ DDDDdddvvv R'R'R'pppp$D_{S+}D_{S+}C$

These data represent the following:

SS	State number
IIII	Station index number
YY	Year
EE	Potential evapotranspiration
M_oM_o	Month
D_aD_a	Day
sss	Percent of possible sunshine
rrr	Solar radiation

RRR	Total recharge
-D-D-D	Amount by which DDDD becomes negative on a daily basis. DDDD is then restored to zero
PPPP	Precipitation
$e_t e_t$	Total evapotranspiration
$e_s e_s$	Evapotranspiration ("upper" layer)(potential)
$e_S e_S$	Evapotranspiration ("lower" layer)(potential)
$e'_S e'_S$	Evapotranspiration ("lower" layer)
QQQQ	Runoff
MMMM	Total water in soil
mmmm	Available water in soil
TT	Temperature
$D_p D_p$	Average dew point
$\%_1\%_1\%_1$	Percent of total water in soil
$\%_2\%_2\%_2$	Percent of available water in soil
DDDD	Soil moisture deficiency ("lower" layer)
ddd	Soil moisture deficiency ("upper" layer)
vvv	Total wind movement per day
R'R'R'	Recharge to "lower" layer
pppp	Vapor pressure deficit
$D_{S+}D_{S+}$	Amount by which DDDD exceeds S on a given day. DDDD is then restored to equal S.
C	Card identification number (optional)

Although the program was written primarily to derive daily values of d and D, the IBM 650 develops many other useful statistics internally for use in computing the final d and D values. Some of these statistics have been extracted from the computations and punched on the output cards. The input data are combined with the various computations on the output cards to facilitate joint statistical analysis of the input data and the derived output statistics.

The additional output data will be of interest to research workers in studying various aspects of the water balance problem. Further, these statistics form a series of data which have climatological significance. The additional data are obtained at virtually no extra cost and serve as a useful check on the information being used for the computation of the final d and D values.

If evapotranspiration (e_t), one of the by-products of IBM 650 Program HHE002, were computed on a daily basis for a network of stations over the United States it is not inconceivable that such information would be extremely valuable in weather forecasting problems involving the transfer of latent heat supplied by the earth during evapotranspiration processes and received by the atmosphere during condensation. Landsberg and Blanc (1957) point out the importance of moisture evaporated from the soil and plants and emphasize the fact that a significant portion of the rainfall over the central and eastern United States, especially shower-type rainfall, consists of water re-evaporated from land areas. Atmospheric moisture originating over ocean areas may fall and evaporate many times in a series of steps or cycles in its movement over land with the general circulation. Thus, soil moisture or evapotranspiration in one area may control to some degree the rainfall in another area. The first computations with IBM 650 Program HHE002 as outlined above took place at the Computation Center, Rutgers University, New Brunswick, N. J. on April 21, 1958. A complete and detailed manual (Engelbrecht, 1958) has been written for the use and operation of IBM 650 Program HHE002. The output data cards as described above are produced at the rate of 12 1/2 cards per minute, 750 cards per hour, or 3650 cards (10 years of daily cards) in approximately 5 hours.

ACKNOWLEDGMENTS

The author wishes to express appreciation to Max A. Kohler, Chief Research Hydrologist, U. S. Weather Bureau, for valuable suggestions in reviewing the manuscript of this paper, and to James K. McGuire, Northeast Area Climatologist, U. S. Weather Bureau, A. Vaughn Havens, Department of Meteorology, and Fred G. Fender, Director, Computation Center, Rutgers University, for their interest and helpfulness in connection with the testing of the program on an unsponsored basis at Rutgers University. The author is also grateful to O. E. Street, Professor in Agronomy, University of Maryland, for his interest and helpfulness in getting the IBM 650 program and test data punched on IBM cards.

REFERENCES

Engelbrecht, Howard H., "Manual for Use of IBM 650 Program HHE002 - Potential Evapotranspiration and Soil Moisture Accounting (Kohler Method)," U. S. Weather Bureau, Friendship International Airport, Baltimore, Md., July 1958.

Hamon, Russell W., Weiss, Leonard L., and Wilson, Walter T., "Insolation As an Empirical Function of Daily Sunshine Duration," Monthly Weather Review, vol. 82, No. 6, June 1954, pp. 141-146.

Kohler, M. A., "Meteorological Aspects of Evaporation Phenomena," Proceedings General Assembly, IUGG, Toronto, Canada, Sept. 1957, vol. 3, pp. 421-436.

Kohler, M. A., Nordenson, T. J., and Fox, W. E., "Evaporation from Pans and Lakes," U. S. Weather Bureau Research Paper No. 38, May 1955.

Landsberg, H. E. and Blanc, Milton L., "Interaction of Soil and Weather," Soil Science Society of America, Proceedings, vol. 22, No. 6, Nov.-Dec. 1958, pp. 491-495.