MEASUREMENT AND EVALUATION
OF EVAPORATION IN
OKLAHOMA

By

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PREFACE

Water contributes, directly or indirectly, to satisfying more human wants than any other natural resource. It is an absolute necessity to the functioning of the human body, with regular daily supplies as important as food. It is essential to the maintenance of all plant and animal life. In varying degree, water is vital in all segments of our economic activity.

Because water is so necessary to life on earth, and human development in many regions is restricted for the lack of it, conservation and proper use of the available supplies become of primary importance. Numerous studies have been made on the losses of water by runoff and vigorous steps have been taken to reduce this loss. Water losses through evaporation, however, are not so obvious and only a few scientists have made an effort to measure the occurrence and evaluate the importance of this phenomenon.

The purpose of this study is the investigation of the climatological factors contributing to the process of evaporation within Oklahoma, and the derivation of a formula, based on this data, to compute the amount of evaporation. The results of such a study should provide an intimate knowledge of the relationships between the variables contributing to the evaporation process. This knowledge will provide a means to evaluate the present system of evaporation measurement within Oklahoma as practiced by the United States Weather Bureau, and give basis for recommendations to improve this program.

Indebtedness is acknowledged to the staff of the Geography Department of the Oklahoma Agricultural and Mechanical College, and especially to Drs. Robert C. Fite and Edward E. Keso for their valuable criticism and guidance. Indebtedness is also acknowledged to Professors Carl Marshall and A. W. Wortham of the Statistical Laboratory, and to Professor William E. Hardy of the Department of Meteorology for the use of meteorological data and equipment.

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INTRODUCTION

Moisture continually evaporates into the air from exposed land and water surfaces. The vapor is then transported according to atmospheric circulation until it is condensed into clouds and fogs and a part is precipitated as rain or snow. A part of the moisture precipitated is returned by runoff to its original and ultimate source, the oceans, thus completing the hydrologic cycle.

We recognize that the hydrologic cycle consists of four phases: evaporation, condensation, precipitation, and runoff (Figure 1). Herein an attempt has been made to examine one phase of this cycle, that of evaporation, in order that its effect on our well-being might be better understood.

Evaporation, as used herein, is the natural process of water changing to a vapor. This process occurs under most natural conditions on the face of the earth and in all parts of the world. Losses of water by evaporation are not felt greatly in wet or humid climates, since there is an excess of precipitation. In less humid regions, however, moisture losses by evaporation constitute a highly important factor.

Evaporation is the means by which the moisture that is precipitated upon the earth is returned to the atmosphere. Evaporation consists of transpiration from vegetation, and direct evaporation from water and snow surfaces, and from the soil.

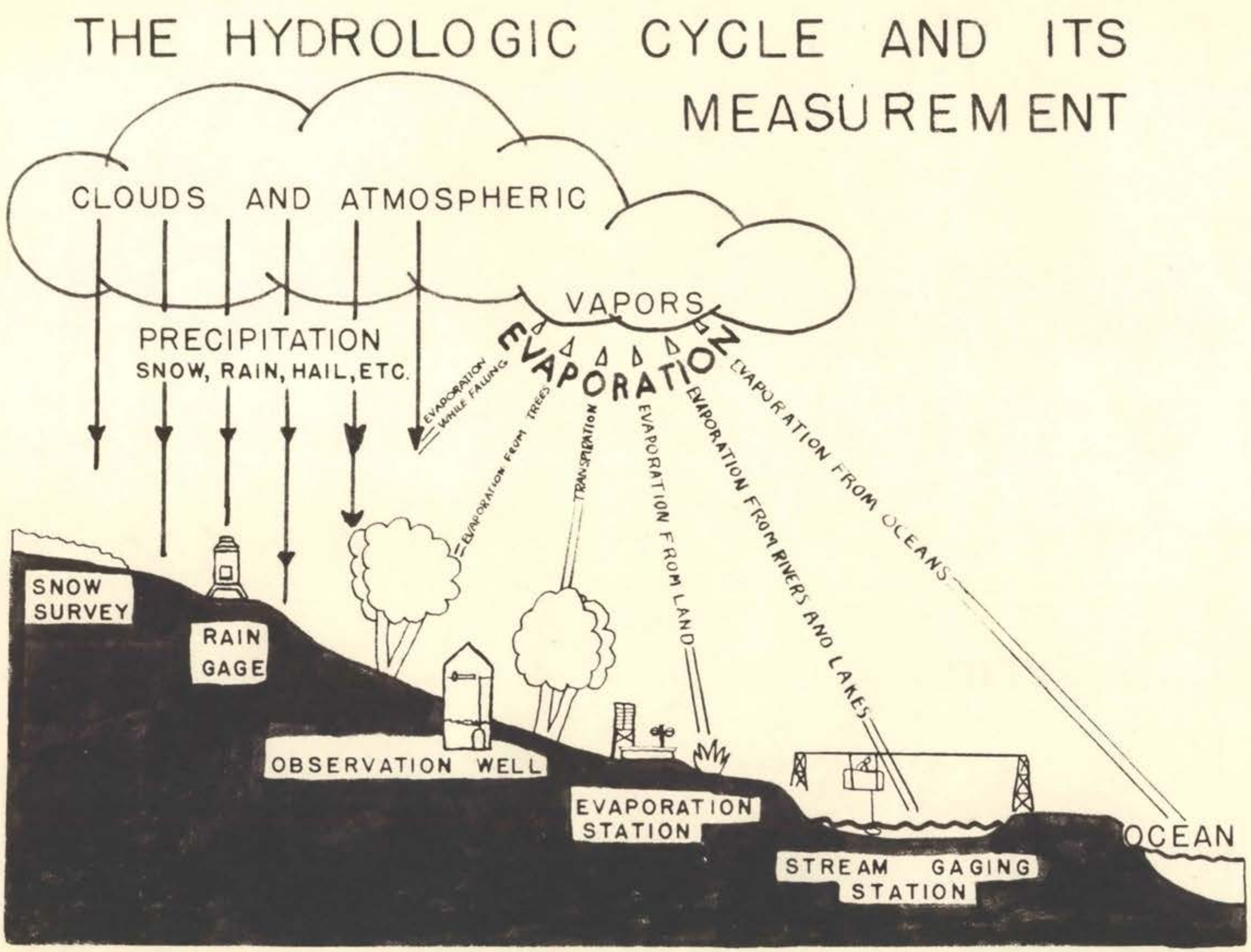
THE HYDROLOGIC CYCLE AND ITS MEASUREMENT
CLOUDS AND ATMOSPHERIC
VAPORS
PRECIPITATION
SNOW, RAIN, HAIL, ETC.
EVAPORATION
EVAPORATION WHILE FALLING
EVAPORATION FROM TREES
TRANSPIRATION
EVAPORATION FROM LAND
EVAPORATION FROM RIVERS AND LAKES
EVAPORATION FROM OCEANS
SNOW SURVEY
RAIN GAGE
OBSERVATION WELL
EVAPORATION STATION
STREAM GAGING STATION
OCEAN

FIGURE 1

The rate at which water is evaporated depends on the influences of several factors, the generally recognized ones being: temperature, humidity, wind movement, and the amount of moisture available to the process.

The total amount of evaporation which takes place in the world has long been a subject of speculation. Wust and Sverdrup, working on this problem, have obtained the following data:

Evaporation from Oceans.	334,000 km^3 per year
Precipitation on Oceans.	297,000 km^3 per year
Amount supplied to the Oceans by runoff.	37,000 km^3 per year.

Their amounts for land surfaces are as follows:

Precipitation on land.	99,000 km^3 per year
Evaporation from land surfaces and inland waters	62,000 km^3 per year.[1]

In 17 western states, the net water loss from all phases of evaporation has been roughly estimated to exceed 30 million acre-feet per year.[2] This would amount to enough water to irrigate 18,000 square miles of arid land, an area equal to nearly half the state of New York.[3] More than half this loss is evaporation from reservoirs, lakes, and flowing water, approximately 15 million acre-feet being lost from reservoirs alone.[4]

Lake Overholser, municipal reservoir of Oklahoma City, Oklahoma, loses roughly 25 million gallons of water each hot, windy, summer day to

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[1]F. A. Berry, Jr., E. Bollay, and Norman R. Beers, Handbook of Meteorology (New York, 1949), pp. 737-745.

[2]Acre-foot. A Unit volume of water equal to the volume of a prism one foot high with a base one acre in area containing 325,850 gallons.

[3]United States Department of the Interior, Geological Survey, Water-Loss Investigations: Volume I, Lake Hefner Studies, Technical Report, Circular 229 (Washington, D. C., 1952), p. 1.

[4]Ibid., p. 1.

evaporation.[5] Each new reservoir increases this loss through evaporation, yet they save water which otherwise would be lost through runoff and make it available for use when needed.

The rate at which evaporation takes place from soils in any given region has a marked influence upon the quantity of rainfall necessary for successful dry farming. Within the drier portions of Oklahoma the disposition of the rainfall has been computed by H. H. Finnell to be as follows:

> The disposition of a 17 inch rainfall on what is termed level land has been roughly determined by a set of experiments carried so that accurate measurements could be made. An average of 31.3 percent of the rainfall comes in showers too small to add anything to the subsoil moisture and evaporates soon after falling. The remaining 68.7 percent of moderate to heavy rains goes as follows: 13.5 percent runs off or collects in low spots in the fields, 34.5 percent evaporates from the surface before it has a chance to soak in deep enough to be safe, 20.7 percent soaks into the soil and joins the permanent body of soil moisture.[6]

Water losses through transpiration from vegetation are estimated to equal or be greater than those losses by evaporation from water bodies.[7] A great deal of the moisture lost by transpiration is hardly beneficial to man when transpired by noxious plants which contribute nothing except to provide vegetative cover for the land.

The importance of evaporation as related to the present economic and future economic status of the Southwest cannot be denied. If present forecasts regarding new industries and the subsequent population growth

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[5] "Nature's Drain on City Water," Daily Oklahoman, October 25, 1953, p. 27.

[6] H. H. Finnell, Heavy Plains Soil Moisture Problems, Oklahoma Agricultural Experiment Station Bulletin 193 (Stillwater, Oklahoma, 1929), p. 1.

[7] A. A. Young and Harry Blaney, Use of Water by Native Vegetation (Sacramento, California, Bulletin 50, 1942), p. 2.

are reasonably correct, water may well become the most important raw material of this section of the United States.[8]

Evaporation of moisture, as a natural process, is unaffected by political boundaries or cultural features and deserves much more attention from geographers and climatologists than it has previously received. The factors contributing to the evaporative process serve to make it an ideal expression for the climate of a region as it affects our welfare.

Purpose and Method of This Study

In this study an attempt is made to derive a rational expression for evaporation rates from water bodies in Oklahoma and to evaluate the present system of evaporation measurement as conducted by the United States Weather Bureau.

Assuming that both goals have a common relationship, the following procedure was used:

a. Selection of Stations. The stations (10 in number) used in this study were chosen from the existing 17 stations on the basis of length of record and geographical location.

b. Computation and transcription of data from records. The data was compiled from the monthly and annual issues of the Oklahoma section of *Climatological Data* published by the United States Weather Bureau. This data was then recorded on IBM punch cards to facilitate computation and tabulation through the use of IBM machines.

When this primary procedure had been completed the following relationships were sought:

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[8] "Increased Population Forecast for Southwest," *Daily Oklahoman*, February 21, 1954, p. 31.

a. The relationship between the wind movement and the rate of evaporation.

b. The relationship between the average monthly temperature and the rate of evaporation.

c. The relationship between the monthly precipitation and the rate of evaporation.

d. These relationships (a to c) were grouped and used in the derivation of a formula for the computation of evaporation.

The evaporation formula obtained from the computations in the previous paragraph was applied to an extensive monthly series from each station, with the compiled result being compared with the actual recorded evaporation. The evaluation of this series was used to evaluate the program of the Weather Bureau within the state.

CHAPTER II

THE NATURE OF EVAPORATION

Within Oklahoma, evaporation is measured at 17 sites ranging from Goodwell in the Northwest, (Figure 2) to Wister Dam in the Southeast, and from Altus Dam in the Southwest to Grand River Dam in the Northeast. As a whole, the distribution of these stations is fairly satisfactory. However, a more complete climatic picture of the state could be obtained if two or more additional stations were located in the Southeast quadrant of the state.

Evaporation, as measured at these sites, varies from a monthly average of 5.74 inches at Wister Dam in the east to 11.17 inches at Goodwell in the Oklahoma Panhandle. Within the state, precipitation varies inversely with the evaporation, Wister Dam having a monthly mean of 3.73 inches while Goodwell has 1.46 inches per month.

Transpiration

Transpiration is the evaporative term for the process by which the water within plants is transferred to the atmosphere as water vapor. Whether or not the process is necessary to plant life is subject to argument.[1] However, it may be wasteful in that many plants transpire quantities of water vapor without performing any useful purpose on earth.

Acquatic vegetation excepted, most plants obtain their water supply from the soil through their roots. The rate at which plants absorb

[1] Ray K. Lindsley, Max A. Kohler, and J. L. H. Paulhus, Applied Hydrology (New York, 1949), p. 169.

U.S. WEATHER BUREAU EVAPORATION STATIONS IN OKLAHOMA

FIGURE 2

moisture from the soil depends on the nature of the plant, the capacity of the soil to provide water to the root systems, and the degree to which atmospheric conditions favor transpiration.

When moisture is not furnished to the root system as fast as transpiration withdraws it from the plant structure, plant wilting occurs. Plant wilting is not a true indicator of soil moisture deficiency, however, as conditions are often severe enough to cause minor wilting with a maximum of soil moisture present.

Transpiration ratios are ratios of weights of water consumed by plants during the growing season to weights of dry matter produced (Table I). Most investigators of water consumption by crops have computed transpiration ratios on the basis of total dry matter, exclusive of roots, except for root crops. Although growing plants contain relatively large proportions of water, usually from 65 to 90 percent, by weight, actual quantities present at time of harvest are negligible in comparison with the total quantities consumed during growth.[2]

Evaporation From Soils

Soil moisture is very important to crop production. No plant can grow unless moisture is available to deliver food and insure regular plant functions. In arid regions the growth of plants is hindered more by the lack of moisture than by any other factor. Even in humid regions, crop yields are often substantially reduced by periods of droughts.

In regions where only a small amount of precipitation falls, practically all that is absorbed by the soil returns to the soil surface to be evaporated directly or to pass through the plant before being evaporated. Plants growing in arid regions, adequately supplied with

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[2] Ibid., p. 170.

TABLE I

MEAN TRANSPIRATION RATIOS OF CROPS*

Plant Species	Ratio Based on Dry Matter
Grain Sorghum.	304
Corn	349
Sugar Beets.	443
Barley	518
Buckwheat.	540
Common Wheat	557
Cotton	568
Potatoes	575
Oats	583
Rye.	634
Rice	682
Legumes.	750
Flax	783

*Source: Lindsley, Kohler, and Paulhus, Applied Hydrology, p. 174.

irrigation water, transpire more water than similar plants growing in humid regions.

As a rule, rates of soil evaporation increase with wetness of the soil until the amount of moisture, by weight, is approximately 26 percent.[3] After this amount has been reached there is little increase in evaporation rates with increases of moisture.

Moisture evaporated from the soil is lost to the use of crops. Hence, it is important that the evaporative processes be minimized, to insure efficient use of available moisture. It has been estimated that throughout the Great Plains, the retention of one additional inch of

[3] F. S. Harris and J. S. Robinson, "Factors Affecting the Evaporation of Moisture from the Soil," Journal of Agricultural Research: VII (December 4, 1910), p. 439.

precipitation within the soil would result in increased wheat yields of three to four bushels per acre.[4]

Evaporation from Water Surfaces

Evaporation from water surfaces comprise approximately half the total water lost to evaporation each year.[5] The process causes losses of water that otherwise would be available for beneficial use. In humid regions, precipitation is usually great enough to satisfy requirements. In such regions, losses from exposed water surfaces are important but seldom critical. In arid regions, where precipitation is often too low to maintain plant growth, evaporative losses are highly important factors in determining the feasibility of constructing water storage units for use in supplemental irrigation.

The industrial, urban, and to a great degree, agricultural well-being of the United States depends upon reservoir storage. In the arid and semiarid regions of the United States, where the stream flow is derived mainly from the runoff of melted snow, 75 percent or more of the total annual runoff flows out of the drainage basin in a huge wave, whose base may last for several weeks or more, but whose crest is far ahead of peak demands.[6] In humid areas, 50 to 70 percent of the total annual runoff occurs in the form of stream rises from fains and melting snow. The other 30 to 50 percent is derived from ground water whose flow is usually comparatively steady.

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[4]United States Department of Agriculture, Soils and Men, Yearbook of Agriculture (Washington, D. C., 1938), p. 681.

[5]United States Department of the Interior, Geological Survey, Water-Loss Investigations: Volume 1, Lake Hefner Studies, Technical Report, Circular 229 (Washington, D. C., 1952), p. 1.

[6]House of Representatives, United States Congress, The Physical and Economic Foundations of Natural Resources (Washington, D. C., 1952), p. 41.

Without artificial storage, only one-half or less of the runoff in humid areas can be depended upon for regular use, and in arid and semi-arid areas, only a small part of the total runoff can be used beneficially.[7]

By storing the water accumulated in flood rises, damaging floods can be avoided, and the flow can be synchronized more closely with the demands of municipal water supply, power, and irrigation activities.

The storage of water makes possible the utilization of water that otherwise would flow unused to the sea. However, the toll exacted by the process of evaporation from storage reservoirs is great. This could be reduced somewhat by a shift in the design of storage units to increased depths of storage units with resulting reduced surface exposure.

Problems of Evaporation Measurement

Because evaporation plays such a large part in the hydrologic cycle and in the determination of our well-being, a great deal of time and effort has been spent in attempting to find a means of measuring it directly. The most direct approach to the computation of evaporation from a water body would be the measurement of the outflow and inflow, with evaporation being the difference. However, the measurement of these two components are extremely difficult. The outflow component would include seepage, which is impossible to measure. Moreover the degree of accuracy in these measurements would need to be high or the error could conceivably exceed the evaporation.

Due to these difficulties, investigators have designed instruments to measure the evaporative power of the air and not the actual evaporation. The evaporative power being a measure of the degree to which a

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[7] *Ibid.*, p. 41.

a region is favorable or unfavorable to evaporation.[8]

The use of pans or tanks as evaporimeters raises some important problems in the correlation of data from such an instrument with actual evaporation from a soil surface or a water body. It has been found by observation that rates of evaporation differ between the various evaporation pans in use due to the differences in exposure of the pans, that of surface exposure being the most important.[9] The causitive factors of evaporation from evaporation pans are considerably affected by the dimensions, shape, and exposure of the pan with respects to the surrounding elements on the earth's surface and to the water body.[10] These factors are summarized in Table II by grouping into evaporation coefficients.

TABLE II*

EVAPORATION REDUCTION COEFFICIENTS FOR EVAPORATION PANS IN COMMON USE

Type of Pan	Reduction Coefficient
Actual Pan Evaporation	1.00
United States Weather Bureau Class A Pan	0.69
Bureau of Plant Industry Pan	0.91
Colorado Sunken Ground Pan	0.78
Floating Pan	0.80

*Source: A. A. Young, pp. 34-40.

The United States Weather Bureau Class A evaporation pan was first used in the Western states in 1916, and its records are the most numerous

[8] Lindsley, Kohler, and Paulhus, p. 160.

[9] Ibid., p. 160.

[10] Ivan E. Houk, Irrigation Engineering (New York, 1948), p. 258.

of any single type.[11] As a result, they are especially valuable for comparative study and research.

The pan is four feet in diameter, ten inches deep, made of galvanized iron and set on two-by-four-inch timbers, which permit free air circulation beneath the pan. A still well in the pan permits measurement, by use of a hook gage, the amount of water evaporated (Figure 3). Depth of water in the pan should not be less than seven inches nor more than eight inches. Since the pan is fully exposed, the water within warms up rapidly in the morning and cools rapidly after sundown. During the daytime it has a high rate of evaporation which exceeds that of any other pan in common use.

The pan maintained by the Bureau of Plant Industry at its numerous plant experiment stations throughout the West is six feet in diameter, 24 inches deep, made of iron, and set 20 inches in the ground with the level of the water within the pan equal to the outside ground level. Measurement of evaporation losses are made by means of a hook gage in an outside still well. Because this pan is set into the ground and contains a greater amount of water than the Class A pan, its temperatures are cooler during the day and warmer at night. Consequently, the evaporation is less than from the smaller, more exposed pan.[12]

The Colorado Sunken Ground Pan was first used in Colorado in 1890 and has been in continuous operation ever since. The pan is three feet square, 18 inches deep, and set 14 inches in the ground with the water level in accord with the ground level. Evaporation losses from this pan are measured in the same manner as from the Bureau of Plant Industry pan.

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[11] A. A. Young, Evaporation From Water Bodies in California (Sacramento, Bulletin 54, 1947), p. 14.

[12] R. E. Karper, Rate of Water Evaporation in Texas, Texas Agricultural Experiment Station Bulletin, Number 484 (College Station, Texas, 1933), pp. 6-7.

U. S. WEATHER BUREAU EVAPORATION STATION EQUIPMENT

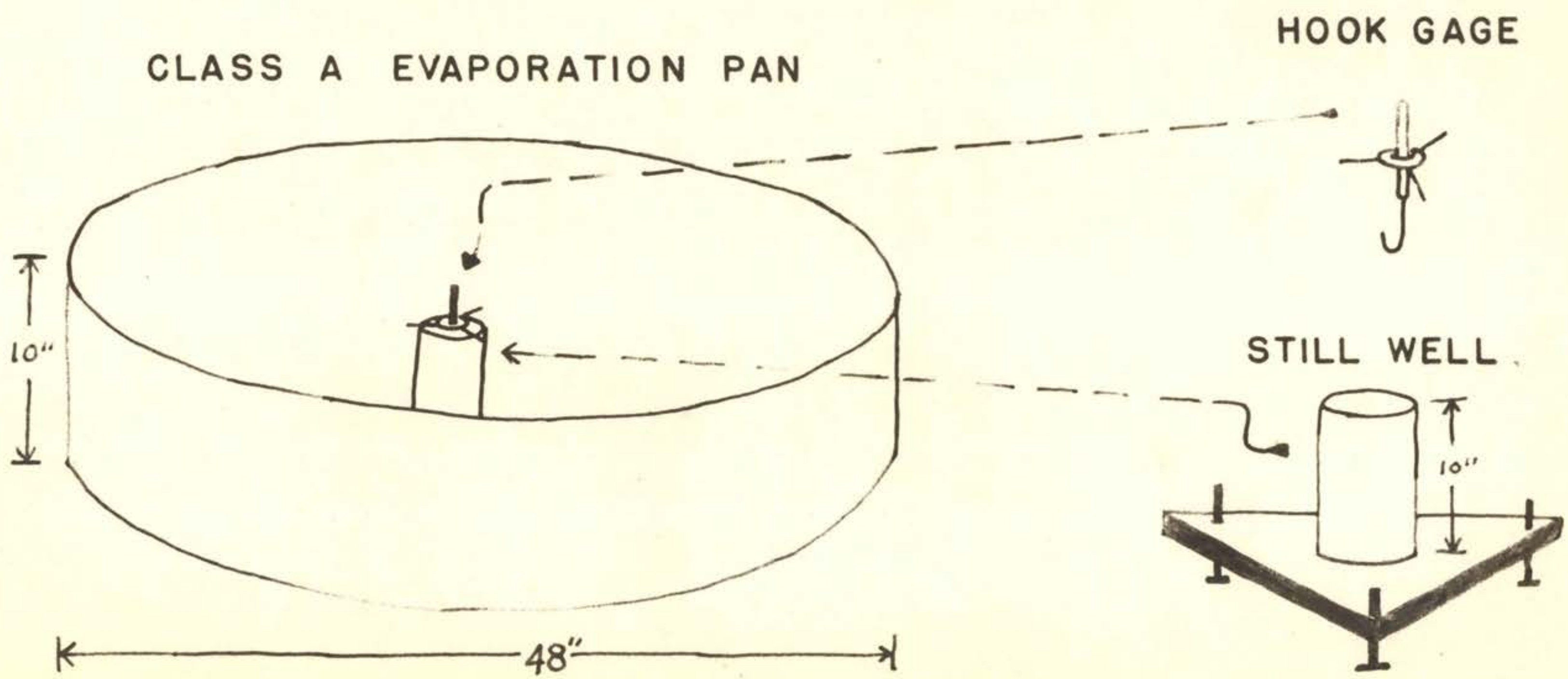

FIGURE 3

The rate of evaporation from this pan is less than from the Weather Bureau pan due to its protection by the ground, but greater than that for the Bureau of Plant Industry pan because of the smaller volume of water within.[13]

The floating pan has the same dimensions as does the Colorado Sunken Ground Pan and is used either on a raft in the middle of a reservoir or lake, or partially submerged in the water. The amount of evaporation is measured by the amount of water required to bring the water level within the pan in accord with a fixed index point mounted in the middle of the pan. The advantages of this pan are that because it is partially submerged the temperature within the pan is more nearly equal to the temperature of the water body, and it is affected by the same conditions of wind, temperature, and humidity that control evaporation from the water body.[14] The disadvantages are loss of record by water splashing in and out of the pan during stormy conditions, and the difficulty in determining the exact amount of precipitation to enter the pan.

The rate of evaporation from different pan types varies widely, and before the evaporation data can be used in estimating the loss from large bodies of water, it is necessary to know the ratio between the evaporation from the type of pan used and that from a large water surface.

Because of the aforementioned difficulty in evaluating actual evaporation from natural surfaces, researchers turned to evaporimeters to measure the evaporation power. To give a wider range of applicability to these evaporimeter records, many investigators derived formulas for the computation of evaporation rates. However, since many of these

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[13]Young, pp. 13-14.

[14]*Ibid.*, p. 14.

formulas are based on evaporimeters whose rates of evaporation are considerably less than unity, caution must be taken to determine the limit of practicability before the application of a particular evaporation formula to the existing data.

Existing Evaporation Formulas. The evaporation formulas now in existence can be divided into two types: those using observed data correlated with existing meteorological elements, and those using a theoretical approach. The first type of equation has been questioned with regard to the accuracy of the correlation between observed pan evaporation and actual evaporation from water bodies.[15] The main criticism of the theoretical approach is that the majority of formulae require instrumentation accuracy to a degree not possible and the results of such formulae cannot be checked against the actual evaporation from natural water bodies for correctness.

Since eddy conductivity is the primary means for saturated air to be removed from the vicinity of the evaporating body, many theoretical investigators have attempted to relate the evaporation to the mechanism of mass transport by turbulent exchange.[16] Thornthwaite and Holzman have derived an equation of evaporation based on this principle under the assumption that a steady-state condition exists, a steady-state condition being one in which the relative humidity is less than saturation at the surface, increasing to saturation at some higher point in the atmosphere.[17] Their formula is:

$$E = \frac{.274\rho\,(q_1 - q_2)(u_2 - u_1)}{T - 459.4}$$

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[15] O. G. Sutton, Micrometeorology (New York, 1953), p. 348.

[16] Ibid.

[17] H. R. Byers, General Meteorology (New York, 1944), pp. 242-245.

Where E is evaporation in inches per hour from a land or water surface installation where two observations are taken, one at 28.6 feet above the ground and the other at two feet elevation, T is the temperature in degrees Fahrenheit; ρ is the density of the air; q_1 and q_2 are the vapor pressures in inches of mercury at the upper and lower levels; and u_2 and u_1 are the wind velocities in miles per hour at the upper and lower levels.[18] This formula is correct for an adiabatic atmosphere. Corrections for other conditions are minor except those for strong inversions.[19]

The transformation of a liquid to a vapor is a physical process requiring heat. For water to remain at a constant temperature while evaporation is taking place, it is necessary that heat be supplied at a rate equal to the cooling by evaporation.[20] In nature, however, this process is not controlled and so allowances must be made for heat gain or loss during the evaporation process.

Cummings and Bowen have derived a series of equations of evaporation based on the heat-balance method.[21] However sound their hypothesis may be, there is little practicability in this work due to the scarcity of information necessary for the solutions of their equations.

Evaporation is expressed as a function of the various atmospheric elements, such as temperature, precipitation, humidity, and wind movement, in many empirical formulas based on observations of evaporation from pans, reservoirs, and lakes. Dalton first recognized the

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[18] C. W. Thornthwaite and Benjamin Holzman, "Measurement of Evaporation from Land and Water Surfaces," Monthly Weather Review, LXVII (1939), 4-11.

[19] F. A. Berry, Jr., E. Bollay, and Norman R. Beers, Handbook of Meteorology (New York, 1949), p. 729.

[20] Lindsley, Kohler, and Paulhus, p. 167.

[21] Ibid.

relationship between the evaporation and the vapor pressure in 1802.[22] Since that time, this relationship has been the basis for a variety of formulas. Only two such formulas will be discussed here.

Carl Rohwer, at Fort Collins, Colorado, conducted perhaps the most intensive study of evaporation of the 1930's, using both available evaporation measurements and results from controlled laboratory experiments. His empirical formula is:

$$E = [0.44 - 0.118W][e_s - e_d]$$

where E is the daily evaporation in inches from a water body; W is the mean velocity of the surface wind in miles per hour; e_s is the mean saturated vapor pressure at the temperature of the water surface in inches of mercury; and e_d is the mean saturated vapor pressure of the air at the temperature of the dewpoint in inches of mercury.[23]

Adolph Meyer, working under somewhat similar conditions derived the following formula:

$$E = C\left[V_w - V_a\right]\left[1 - \frac{W}{10}\right]$$

where E is the evaporation in inches per 30 day month; V_w is the saturation vapor pressure in inches of mercury, corresponding to the mean monthly air temperature; V_a is the average monthly vapor pressure of the air, computed from the mean monthly air temperature and the mean monthly relative humidity; W is the mean monthly wind speed in miles per hour; and C is an empirical constant having a value of 11 for reservoirs and deeper lakes, and a value of 15 for pans, puddles, shallow reservoirs,

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[22] A. F. Meyer, Elements of Hydrology (New York, 1928), p. 206.

[23] Carl Rohwer, Evaporation From Free Water Surfaces, United States Department of Agriculture, Technical Bulletin 271, 1931, p. 2.

and vegetation.[24]

Recognized Factors Affecting Evaporative Surfaces

The factors most generally recognized as affecting evaporative surfaces are temperature, relative humidity, wind movement, and character of the surface.

These factors will be discussed with regard to their effect on evaporation from water surfaces. Evaporation from soils and transpiration are affected by the same factors, but require special consideration.

Characteristics of Water Surfaces. The rate at which water particles leave the water surface and enter the atmosphere depends upon the temperature of the water and the relative humidity of the air. The relative humidity being the ratio of the actual moisture present in the air to the moisture required for the air to become saturated at a constant temperature.[25]

When the temperature of the air is warmer than that of the water, and the relative humidity is less than saturation, evaporation will occur at a relatively high rate. As the process proceeds, assuming a calm atmosphere, the amount of moisture in the air will increase progressively and the rate of evaporation will decrease at approximately the same rate.

When the air is saturated no evaporation will occur except during conditions favoring supersaturation.[26]

The effect of wind velocity on the rates of evaporation is directly related to the displacement of moist air from over the evaporating body

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[24]Adolph Meyer, Evaporation from Lakes and Reservoirs (Minneapolis, 1942), p. 12.

[25]Byers, p. 62.

[26]Lindsley, Kohler, and Paulhus, p. 155.

by drier air. The rapidity of this exchange of air increases evaporation until a limiting velocity is reached.

Atmospheric pressure is closely related to other factors affecting evaporation and it is difficult to state the effect of its variations on the evaporative process. However, due to the decrease in atmospheric pressure with height, there is a tendency for evaporation to increase. This increase is offset by the general decrease in surface temperatures associated with elevations.[27]

Characteristics of Vegetative Surfaces. The rate of loss of water from plants by transpiration varies with the type of plant, the conditions under which it grows, the time of year, and the climatic conditions from year to year. These factors can be classified as physiological or environmental.

Physiological factors include cuticular transpiration, i.e., transpiration through the cuticle into the atmosphere; stomatal transpiration, i.e., transpiration through the pores of the plant leaf; and guttation, i.e., the loss of water in liquid form through the leaves and plant stems.[28]

Since transpiration is essentially the evaporation of water from leaf cells, its rate is materially influenced by the same factors which influence evaporation from water surfaces. Hence, high temperatures, low humidities, and brisk winds all tend to increase transpiration unless wilting takes place. Solar radiation influences transpiration in that it controls the permeability of the plant structure, the opening of the stomata, and furnishes the principal heat source for evaporation.[29]

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[27] Ibid., p. 157.

[28] Oscar E. Meinzer, ed., Hydrology (New York, 1949), p. 260.

[29] Lindsley, Kohler, and Paulhus, p. 172.

Release of moisture by transpiration occurs mainly during the daylight hours of the growing season. Probably not more than five to ten percent of the total daily transpiration occurs at night. The maximum rate of transpiration is reached shortly after noon and the minimum value is reached just before sunrise.[30]

Rates of transpiration and the total amount of water transpired during the growing season differ greatly for various types of plants. Plants growing in arid regions, adequately supplied with water, transpire more moisture than similar plants growing in more humid regions.

Soil conditions affect rates at which moisture can be absorbed by the plant roots, raised through the plant, and made available for transpiration. Plants growing on poor soils consume more moisture than do plants growing on fertile soil.[31]

Changes in rate of transpiration during a particular growing season are caused by development in plant growth and variations in available water supply, as well as by changes in weather conditions. When adequate moisture supplies are available, daily rates of transpiration increase until approximately the middle of the growing season, then decrease gradually until the crop is harvested.

Characteristics of Soil Surfaces. Soil evaporation is the loss of water by evaporation into the atmosphere from water films adhering to the soil grains.[32] It usually occurs at the surface of the ground, but if the cracks in the soil are large enough, it may occur within these cracks as interior evaporation.

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[30] Houk, p. 296.

[31] *Ibid.*, p. 297.

[32] *Ibid.*, p. 286.

The most important factor controlling the rate of evaporation from land areas is the temperature of the air and of the exposed moisture.[33]

Another factor affecting the rate of evaporation from a soil surface is the availability of the water. As long as the surface is saturated, the evaporation rates are similar to evaporation from a water body. When the soil surface is not saturated the rate of evaporation is limited by the rate at which the moisture is drawn to the surface, even though the existing meteorological conditions may favor higher rates of evaporation.

Other factors which are important in determining evaporation rates include humidity and wind movement.

Since the role of all these elements is affected by the nature of the soil, and the type and density of the vegetation growing on the soil, any factor which alters the surface, alters the evaporation rate. Vegetation, by shading the soil, reduces the temperature and consequently the rate of evaporation.[34] This reduction, however, is more than offset by the rate of vegetative transpiration. Vegetation also limits direct evaporation by protecting the soil from wind movement and retarding the replacement of moist air with drier air. These factors tend to keep the evaporative losses for soil having a dense vegetative cover to a minimum. Evaporation under a forest cover is less than that from a grass cover due to the greater shade produced by the trees.[35]

It is a foregone fact that the evaporation rates are greatest from

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[33] Meyer, p. 229.

[34] Leon Lassen, H. W. Lull, and Bernard Frank, Some Plant-Soil-Water Relations in Watershed Management, United States Department of Agriculture, Division of Forest Influences, Circular 910, October, 1952, p. 17.

[35] Ibid.

the immediate surface of the soil because the particles there are entirely exposed to the effect of the evaporation factors. The rate of movement of the moisture from the lower levels to the surface is regulated by the size and shape of the soil particles. Thus soils composed of large particles and numerous cracks are subjected to higher rates of evaporation than are finer textured soils.[36] In fine textured soils, the capillary effect is felt to greater depths than for the coarser grained soil.[37]

Harris and Robinson, in summarizing their experiment on soil evaporation state:

> Evaporation of moisture increases with the initial quantity in the soil. The increase is not so great with the higher percentages of moisture as with the lower, and there seems to be a number of critical points where the rate of evaporation increases rapidly. The rate of evaporation from moist soil increases rapidly as the humidity of the air decreases. Air currents greatly increase evaporation, but after a certain limit is reached, the rate of evaporation is only slightly increased by increasing the wind velocity. Reducing the intensity of the sunshine has a large effect in reducing the amount of evaporation. Slight changes in the temperature has a marked effect on reducing the amount of evaporation. Compacting of the soil increases evaporation.[38]

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[36] Lindsley, Paulhus, and Kohler, pp. 289-291.

[37] Ibid.

[38] F. A. Harris and J. S. Robinson, "Factors Affecting Evaporation of Moisture from the Soil," Journal of Agricultural Research, VII (December, 1916), 439-461.

CHAPTER III

ANALYSIS OF OKLAHOMA EVAPORATION DATA

The analysis of data was divided into two different procedures: a preliminary analysis and a regression analysis.

The Preliminary Analysis

Data used in this study were compiled from climatological observations made by co-operative observers of the United States Weather Bureau at selected evaporation stations in Oklahoma. These stations were selected on the basis of geographical location, length of record, and the completeness of record. In Table III the names of the stations selected, the counties in which they are located, the length of their record used in this study, and the characteristics of this record are listed.

The climatological observations are normally taken at 7:00 A.M. each day. Data recorded at this time include include the maximum and minimum temperatures for the past 24 hours, the amount and time of precipitation, the miles of wind to pass the evaporation pan, and the amount of evaporation from a Class A evaporation pan.

The length of evaporation observation records is limited at most stations. Only recently (1947) was evaporation measurement emphasized by the Weather Bureau in Oklahoma. Another shortcoming of the records is the yearly break in observations made by certain stations due to the advent of freezing temperatures. However, only two of such stations, Goodwell and Stillwater, were included in this study.

A common fault of most climatological records is that of missing

TABLE III

COUNTY LOCATION AND OBSERVATIONAL CHARACTERISTICS OF EVAPORATION STATIONS USED IN THIS STUDY*

Station	County	Years of Data Used	Character of Record
Fort Supply Dam	Woodward	1941-1953	Yearly
Grand River Dam	Mayes	1941-1953	Yearly
Tipton	Tillman	1941-1953	Yearly
Wister Dam	LeFlore	1948-1953	Yearly
Great Salt Plains Dam	Alfalfa	1948-1953	Yearly
Stillwater	Payne	1948-1953	Seasonal
Goodwell	Texas	1948-1953	Seasonal
Lake Overholser	Oklahoma	1948-1953	Yearly
Altus Dam	Jackson	1947-1953	Yearly
Hulah Dam	Osage	1947-1953	Yearly

*Compiled from Climatological Data, Oklahoma Section.

data. In this experiment there was a possibility of having 924 individual monthly measures, including average temperature, total evaporation, total precipitation, and total wind movement from the ten selected stations. The actual number of complete monthly observations recorded for use was 631, 292 monthly observations (31.6%) having been considered invalid for this study due primarily to missing data.

Temperature. The temperature used in this study is the mean monthly temperature expressed in degrees Fahrenheit (Table IV). This was obtained by adding the monthly maximum and minimum temperatures and dividing by two.

The thermometers used in obtaining the maximum and minimum temperatures are mounted within a regulation Weather Bureau shelter. The height of the thermometers vary from five to six and one-half feet.[1] This height

[1] V. Conrad and L. W. Pollack, Methods in Climatology (Cambridge, Massachusetts, 1950), p. 14.

TEMPERATURE AND PRECIPITATION REGIMES FOR SELECTED OKLAHOMA STATIONS

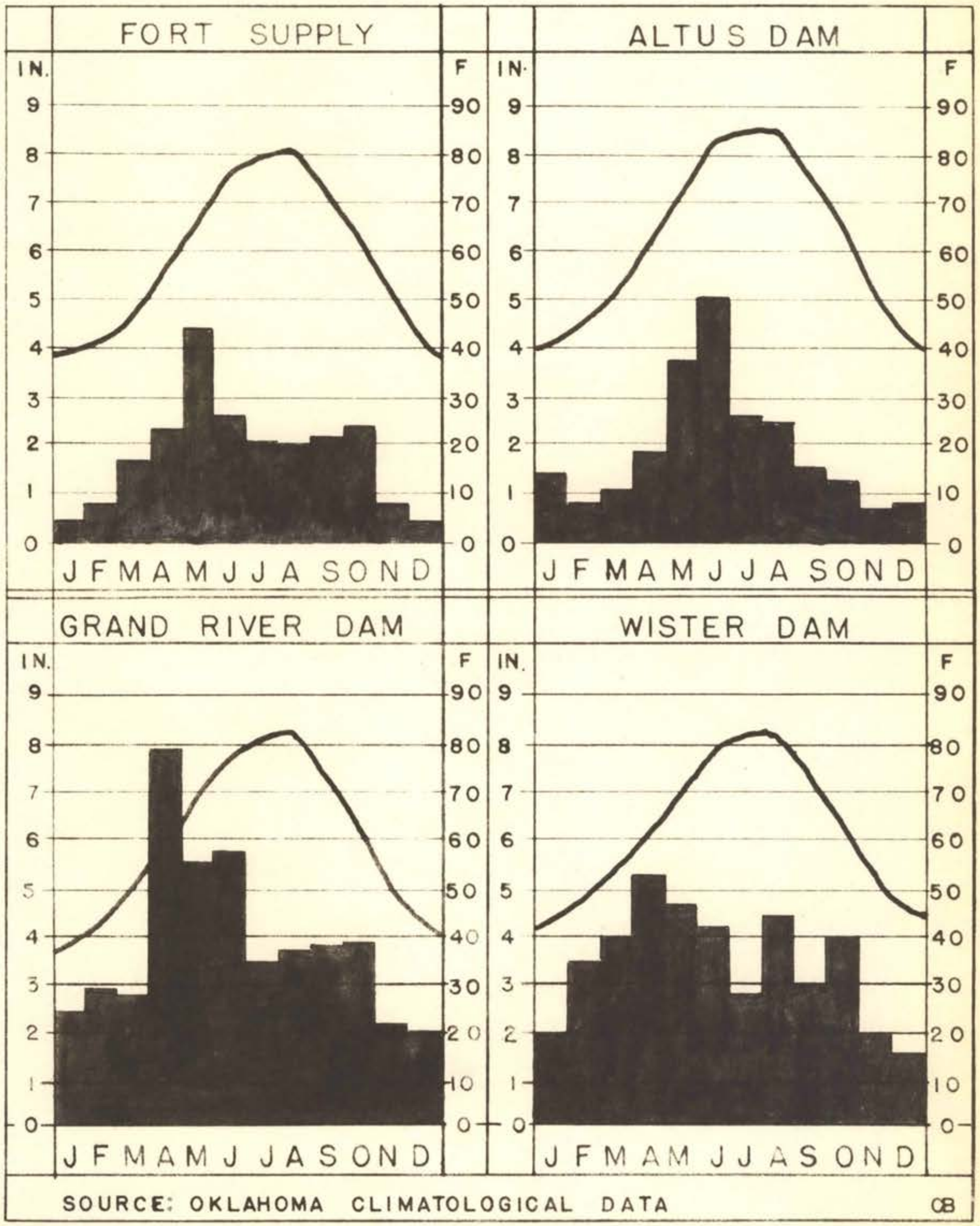

FIGURE 4

AVERAGE MONTHLY EVAPORATION & WIND MOVEMENT AT SELECTED OKLAHOMA STATIONS

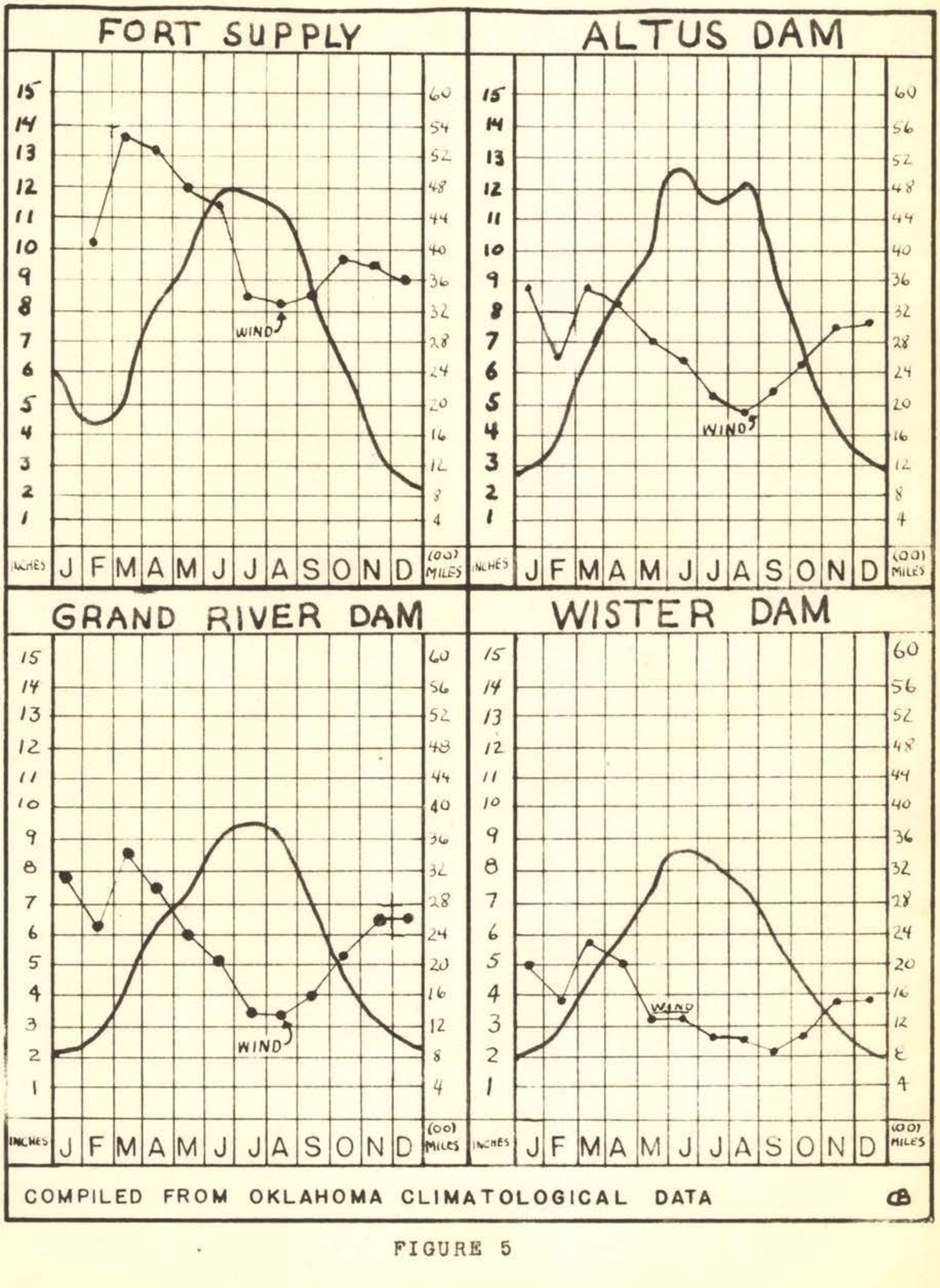

FIGURE 5

TABLE IV

MEAN MONTHLY TEMPERATURE AT SELECTED OKLAHOMA STATIONS
(In Degrees Fahrenheit)

Month	Grand River Dam	Tipton	Wister Dam	Great Salt Plains Dam	Stillwater	Goodwell	Lake Overholser	Altus Dam	Hulah Dam	Fort Supply Dam
January	38.2	46.4	42.8					40.9	37.9	39.0
February	41.4	45.7	46.7	44.9				46.5	43.2	40.4
March	49.2	50.5	52.8	47.0				51.2	46.8	46.2
April	61.1	60.0	61.4	58.0	57.5	56.6		61.9	58.0	58.3
May	68.9	70.2	70.0	68.7	68.7	65.4		71.5	67.5	66.3
June	77.5	80.5	78.9	79.8	78.7	76.3	83.3	82.6	77.0	77.4
July	80.4	83.2	81.7	81.0	80.0	78.7	80.5	84.3	77.8	79.8
August	81.1	83.5	81.7	81.3	77.9	77.8	78.5	84.4	79.7	81.1
September	71.6	74.4	73.5	73.3	71.5	70.7		75.9	72.9	72.4
October	62.7	62.2	64.0	63.6	63.1	58.6		66.5	63.2	62.4
November	49.1	50.8	51.4	46.7	50.6			50.2	47.7	50.1
December	41.4	43.4	42.2	38.2	41.5			42.6	40.7	40.5

is a decided drawback to the correlation of the temperature with the evaporation due to the height disparity between the two instruments.

Wind. Wind data utilized within this study was the total amount of wind in miles to pass the evaporimeter surface (Table V).

This wind is measured by means of a Robinson three cup anemometer, mounted on the northwest corner of the evaporation pan base, with the cups approximately 18 inches above the water surface. The anemometer is equipped with a gage which records the total number of miles of wind to pass the pan. The gage is read to the nearest whole mile each day when the regular observation is taken.

There is an error in the mileage recorded by this type of instrument due to the weight of the cups and cup arm. This weight tends to cause the record to lag during periods of very light winds, while the built up momentum of the cups and cup arm during periods of gusty winds causes higher values to be recorded.[2]

Precipitation. The precipitation used within this study is the total monthly precipitation, measured to the nearest one-hundredth of an inch (Table VI).

Evaporation stations of the Weather Bureau are equipped with two precipitation gages, one to record the amount of precipitation and the other to record the time of occurrence.

The measurement of the precipitation by these gages is usually accurate, however, when precipitation is accompanied by high winds, the amount received by the precipitation gages is not always correct. This is due to the force of the wind flattening the trajectory of the precipitation particle, making its course more parallel to the collection surface

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[2] A. E. M. Geddes, Meteorology (London, 1946), p. 124.

TABLE V

MEAN MONTHLY WIND MOVEMENT AT SELECTED OKLAHOMA STATIONS
(In Miles)

Month	Stations									
	Grand River Dam	Tipton	Wister Dam	Great Salt Plains Dam	Stillwater	Goodwell	Lake Overholser	Altus Dam	Hulah Dam	Fort Supply Dam
January	3,216		2,061					3,569	2,698	8,110
February	2,559		1,528	3,252				2,655	2,440	4,553
March	3,444	4,148	2,356	4,575				3,555	3,485	5,486
April	2,898	3,799	2,006	4,371	3,873	5,644		3,326	4,299	5,350
May	2,426	4,092	1,387	3,560	3,156	4,746		2,834	2,152	4,827
June	2,143	3,686	1,275	3,538	2,809	5,169	2,584	2,630	1,815	4,658
July	1,447	2,714	1,069	3,065	1,968	4,550	1,667	2,133	1,385	3,493
August	1,405	2,625	1,004	2,794	1,644	3,844	1,224	1,983	1,416	3,339
September	1,665	2,866	918	3,055	1,878	3,533		2,186	1,340	3,407
October	2,117	2,638	1,002	3,045	2,036			2,500	1,522	3,733
November	2,690	3,055	1,568	3,074				2,900	1,849	3,710
December	2,656	3,012	1,576	3,205				2,947	2,128	3,602

TABLE VI

MEAN MONTHLY PRECIPITATION AT SELECTED OKLAHOMA STATIONS
(In Inches)

Month	Grand River Dam	Tipton	Wister Dam	Great Salt Plains Dam	Stillwater	Goodwell	Lake Overholser	Altus Dam	Hulah Dam	Fort Supply Dam
January	2.46		2.06					1.31	0.92	0.36
February	2.92		2.51	0.40				0.88	1.13	0.86
March	2.81	1.68	3.99	1.38	1.63	0.22		1.08	2.54	1.66
April	7.91	2.72	5.19	2.57	4.66	2.37		1.82	3.39	2.31
May	5.50	4.36	4.71	4.37	3.75	1.71		3.71	3.80	4.28
June	5.74	3.73	4.14	3.58	5.31	4.32	0.94	5.03	3.40	2.60
July	3.39	1.89	2.88	4.47	2.56	3.86	4.22	2.54	4.10	2.11
August	3.83	1.98	4.48	3.06	2.70	0.52	1.83	2.41	2.29	2.04
September	3.88	2.66	3.01	1.52	1.90	0.12		1.50	3.00	2.16
October	3.93	1.83	4.01	1.52	1.24			1.27	1.52	2.30
November	2.13	1.18	2.02	1.68				0.71	1.44	0.87
December	2.01	1.07	1.51	0.23				0.81	1.04	0.46

of the gage. This error can be reduced by the use of wind shields around the gage.

Evaporation. The evaporation used in this study is the total amount of water to evaporate from a Class A evaporation pan, measured to the nearest one-hundredths of an inch (Table VII).

The amount of water to evaporate is measured by use of a hook gage in a still well. The depth of water within the pan is maintained at from seven to eight inches. This water is assumed to be free of oily surfaces, and is not diluted by the use of chemicals.

The errors in evaporation measurement are slight from this type of pan. Maintaining the water level at least two inches below the rim minimizes the losses during high winds and stormy conditions, and keeps birds from drinking the water. The evaporation pan is cleaned at intervals to prevent the formation of algae growth near the surface, which reduces the amount of evaporation.

When the preliminary analysis of data was complete, the data were transcribed on IBM punch cards to facilitate further analysis and evaluation. As a further simplification, the following symbols were assigned to the variables:

T . . . . temperature

P . . . precipitation

W . . . Wind movement

E . . . . evaporation

The order followed in entering the data on the punch cards was: station, month, year, average temperature, total precipitation, total wind movement, and total evaporation.

Since the purpose of this study was the determination of the relationships between the evaporation process and the other variables measured by the Weather Bureau, as well as the derivation of a relationship

TABLE VII

MEAN MONTHLY EVAPORATION AT SELECTED OKLAHOMA STATIONS
(In Inches)

Month	Grand River Dam	Tipton	Wister Dam	Great Salt Plains Dam	Stillwater	Goodwell	Lake Overholser	Altus Dam	Hulah Dam	Fort Supply Dam
	Stations									
January	2.39	4.05	2.34					2.91	1.98	5.49
February	2.41	4.65	2.35	3.27				3.36	3.02	4.25
March	4.60	5.65	4.92	5.14				6.12	4.99	5.47
April	6.36	7.23	6.11	6.95	6.97	7.65		8.58	6.68	8.28
May	7.42	9.82	7.23	8.99	7.79	11.21		9.83	7.06	9.57
June	9.40	12.07	8.73	11.78	10.69	15.16	11.54	12.63	9.32	11.92
July	9.58	12.00	8.10	11.16	9.27	13.52	9.56	11.62	8.90	11.81
August	9.14	11.55	7.88	10.66	8.98	10.91	7.77	12.13	9.23	11.57
September	6.70	8.84	6.05	9.28	7.53	9.12		9.36	7.19	8.79
October	4.73	5.90	4.18	6.59	6.30	7.35		6.47	5.55	6.18
November	3.10	4.10	3.09	3.42	4.80			4.47	3.50	3.96
December	2.20	2.72	1.98	2.05				3.10	2.26	2.16

for the expression of evaporation in terms of the other variables, a means of analysis was required which would provide the necessary data without duplication of effort. The type of analysis which would fulfill these requirements was a multi-variable regression.

The Regression Analysis

Two types of regression analyses, linear or curvilinear, could have been used. However, a search of similar existing evaporation studies indicated that most previous investigators had assumed the relationship between the variables to be linear. Accordingly a linear regression analysis was used in this study.

The linear regression analysis can be divided into two sections. The first section of the analysis determines the relationship between the variables under consideration, and the second section determines a formula relating the action of the independent variables, i.e. temperature, wind movement, and precipitation, to the dependent variable, evaporation.

In Table VIII the procedure followed in the determination of the correlation coefficients is illustrated. The lines in the table are numbered and the method will be explained in detail.

An examination of Table VIII shows that this part of the analysis consists of a set procedure, repeated four times with one less variable considered each time.

Line (1) is the sum of the individual monthly measures.

Line (2) consists of the mean value of the individual monthly measures. It is obtained by dividing the sum from line (1) by the number of observations (631).

Line (3) is the sums of squares and products. The temperature value is the summation of the squared individual items. The other three values of this line consist of the product sum of the temperature times the

TABLE VIII

THE REGRESSION ANALYSIS (SECTION I)

Line		Temperature T		Precipitation P		Wind W		Evaporation E
1	ΣT	41,602.9	ΣP	1824.49	ΣW	1,803,187	ΣE	4789.9
2	$\bar{T}$	65.8274	$\bar{P}$	2.8865	$\bar{W}$	2,853.144	$\bar{E}$	7.57895
3	ΣT^2	2,864,727.95	ΣTP	124,507.876	ΣTW	116,394,260.9	ΣTE	340,455.127
4	C.F.	2,738,608.63	C.F.	120,101.384	C.F.	118,699,063.9	C.F.	315,306.535
5	Σt^2	126,119.32	Σpt	4,406.492	Σtw	-2,304,803	Σte	25,148.592
6	$\sqrt{\Sigma t^2}$	355.13						
7			r_{PT}	0.174	r_{WT}	-0.2092	r_{TE}	0.8336
8			ΣP^2	10,935.5621	ΣPW	4,859,270.1	ΣTE	13,795.702
9			C.F.	5,267.0313	C.F.	5,205,532.67	C.F.	13,826.146
10			Σp^2	5,668.5308	Σpw	-346,262.57	Σte	-30.444
11			$\sqrt{\Sigma p^2}$	75.3				
12					r_{PW}	-0.1565	r_{PE}	-.005
13					ΣW^2	6,106,908.969	ΣWE	14,174,236.10
14					C.F.	5,144,752.140	C.F.	13,666,274.38
15					ΣW^2	962,156.829	Σwe	507,961.72
16					$\sqrt{\Sigma w^2}$	31,018.65		
17							r_{WE}	0.1928
18							ΣE^2	43,541.2886
19							C.F.	36,302.4398
20							Σe^2	7,238.8488
21							$\sqrt{\Sigma e^2}$	85.0814

precipitation, temperature times the wind movement, and temperature times the evaporation.

Line (4) is the correction factor, designed to reduce the crude sum of squares (or products) to a sum of squares (or products) of deviation from their means.[3]

The temperature factor is obtained by squaring the temperature sum in line (1). The correction factor for the other variables is obtained by obtaining the product of the values listed for temperature and precipitation, temperature and wind movement, and temperature and evaporation. Then the sum of squares (or products) is divided by the number of observations (631) and subtracted from line (3).

Line (5) is the sum of squares (or products) of the individual deviations of the variables from their respective means.

Line (6) is the square root of the sum of the temperature deviations from the mean.

Line (7) is the correlation coefficient (r) of the variables, i.e., precipitation, wind movement, and evaporation with respect to the temperature. For reference a general form of the equation used to compute this coefficient is listed below:

$$r_{tn} = \frac{\Sigma T^2 \Sigma n^2}{\sqrt{\Sigma T^2 \Sigma n^2}}$$

Line (8) begins the first duplication of the process just explained. The procedure which will be followed through lines (8) to (12) considers the precipitation as the primary element, instead of the temperature as used in lines (3) to (7). This change in the element receiving direct consideration is a part of the regression analysis design and enables

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[3] D. S. Villars, Statistical Design and Analysis of Experiments for Developmental Research (Dubuque, Iowa, 1951), pp. 439-440.

the investigator to place primary emphasis on each variable considered within any particular study.

The values listed in line (8) are: the sum of squares for precipitation, and the product sum for precipitation times wind movement and precipitation times the evaporation.

Line (9) contains the correction factor. This factor was determined in the same manner as in line (4).

Line (10) is determined by the same procedure as was used in the determination of line (5), and has the same function in the analysis.

Line (11) is the square root of the sum of the precipitation deviations from the mean.

Line (12) is the correlation coefficient (r) of the variables considered with respect to the precipitation.

Lines (13) to (17) consist of the second duplication of the analysis procedure. The analysis procedure is the same followed in the previous two phases with one less variable receiving consideration each time. In this phase the correlation between the evaporation and wind movement is determined.

Lines (18) to (21) contain the last phase of the analysis and the values within this phase were determined in the same manner as for the previous phases. No correlation coefficient is sought here since the previous steps have determined all coefficients of correlation that exist between the variables.

The correlation coefficients obtained in the previous analysis are listed in Table IX. The sign preceding the coefficient indicates whether the correlation is positive or negative. These coefficients were substituted into three equations: A, B, and C. These equations were then solved for T, P, and W.

TABLE IX

CORRELATION COEFFICIENTS OF VARIABLES ANALYZED

Variables	Coefficient
Temperature and Evaporation.	0.8336
Precipitation and Evaporation.	0.0050
Wind Movement and Evaporation.	0.1928
Temperature and Precipitation.	0.0084
Temperature and Wind Movement.	0.1858
Precipitation and Wind Movement.	0.1565

	T	P	W		
A	1	0.174	-0.2092	=	0.8336
B	0.174	1	-0.1565	=	-0.0050
C	-0.2092	-0.1565	1	=	0.1928

Which when solved had the following values:

$$T = 0.9310$$

$$P = -0.1084$$

$$W = 0.3704$$

These values were then substituted into the general linear regression formula, and produced the following formula:

$$E = 0.9310\frac{85.0814}{355.133}(T - 65.8274) - 0.1084\,\frac{85.0814}{75.29}(P + 2.8868)$$

$$- 0.3704\frac{85.0814}{31,018.6529}(W - 2853.144) + 7.599$$

Which when reduced becomes:

$$E = \frac{220T - 123P + W - 9390}{1000}$$

The accuracy of these algebraic manipulations can be checked by the following method. The mean values of the variables are substituted into the reduced equation, changing it to the following form:

$$E = \frac{220(65.83) - 123(2.89) + (2853.14) - 9390}{1000}$$

Which, when solved for E has the value of 7.58, which is identical with the mean value listed for E in Table XI. Hence the algebra can be considered correct.

CHAPTER IV

EVALUATION OF EVAPORATION DATA

In the previous chapter the data were analyzed to gain a knowledge of the relationships existing between the variables considered in this study of the evaporation process. These data were analyzed to learn the coefficients of correlation existing between the variables and a formula to evaluate evaporation in Oklahoma.

Correlation Coefficients

The value of the correlation coefficients varied from a plus 0.8336 to a minus 0.1858. As stated before, the plus or minus connotation of these coefficients indicates, to a degree, the relationship between the variables considered, as well as to the entire analyses. In Table IX the variables were paired and the coefficients of correlation between these pairs were listed. To avoid false impressions it should be remembered that the limits of the correlation coefficient are plus one and minus one, and can never be greater or less than plus or minus one respectively. A correlation coefficient of plus one indicates a perfect positive correlation and a minus one the converse.[1] When the correlation coefficient equals zero, no relationship exists between the variables. In general, the value of the correlation coefficient to the analysis tends to decrease as the coefficient approaches zero. This situation

[1] G. W. Snedecor, Statistical Methods (Ames, Iowa, 1953), pp. 138-140.

occurred within this experiment analysis to a degree. However, the occurrence of small correlation values did not weaken the experiment results to any great extent. Rather, these small values tended to widen application of the evaporation formula. The elimination of these coefficients allows use of the formula, when modified, at any climatological station in Oklahoma.

The coefficient of correlation between the temperature and the evaporation is 0.8336. This is the highest correlation obtained in this study and indicates that temperature has a great influence on the evaporative process. The importance of temperature to this process has already been discussed in Chapter II and it is interesting to note how close the results from this analysis follows the discussion of that chapter. Had the temperature of the evaporating body been available for use in this study, the correlation coefficient would have undoubtedly been higher.

The correlations between the precipitation and evaporation, and temperature and precipitation were low. This indicates that these factors have very little influence on each other.

The effect of the wind on the evaporative process is to replace air over the evaporation unit with drier air from a distance. The correlation coefficient between these variables is 0.1928. This is not a high correlation and indicates that the effect of the wind on the evaporation process is limited.

Evaluation of the Evaporation Formula

The formula derived in Chapter III was:

$E = \frac{220T - 123P + W - 9390}{1000}$, where E is the evaporation in inches per

month from a Class A evaporation pan, T is the mean monthly temperature in degrees Fahrenheit, P is the total monthly precipitation in inches, and W is the total amount of wind movement in miles.

A means to evaluate the method of analysis and the number of variables used in this study exists in the computation of R, the regression variable correlation coefficient. When R is greater than the largest r obtained in the regression analysis, the method of the regression analysis is justified.[2]

This evaluation takes the form:

$R^2 = (r_{te})\ (T) + (r_{pe})\ (P) + (r_{we})\ (W)$, When the values from Table VIII are substituted, this equation becomes:

$$R^2 = (.8336)\ (.93) + (-.005)\ (-.1089) + (.1928)\ (.3704).$$

or

$$R^2 = .8469, \text{ and } R = .9202.$$

This value, $R = .9202$, is larger than the original correlation coefficients obtained, hence, the use of a multi-variable linear regression is justified.

The best possible means of evaluating the evaporation formula exists in the comparison of the computed evaporation with the actual observed evaporation for the same conditions. If such a comparison is made, the result of plotting the individual intercepts of the two sets of data will be a 45° line if the correlation is perfect. This evaluation has been carried still further and the error from this line can be computed as a percentage. See Table X and Figure 6. When the percentage of error exceeds the degree of accuracy desired, the formula will be of no further value.

Further investigations into the validity of the formula can be made by application of the extreme limits of the range of the raw data to the

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[2] G. W. Snedecor, p. 363.

TABLE X

COMPARISON OF OBSERVED EVAPORATION WITH COMPUTED EVAPORATION WITH PERCENT OF DEVIATION

Observed Evaporation (in inches)	Computed Evaporation (in inches)	Deviation	
		Amount	Percent
7.96	7.93	0.03	0.3
8.84	7.13	1.71	19.2
8.59	8.47	0.12	1.4
6.80	7.33	0.53	8.0
6.32	6.41	-0.09	- 1.4
7.29	6.53	0.76	10.7
8.68	8.35	0.33	3.9
5.94	5.88	0.06	0.1
7.07	6.16	0.91	12.8
7.28	7.29	-0.01	- 0.1
5.69	6.36	-0.67	-11.9
5.52	5.27	0.25	4.7
7.10	7.56	-0.46	- 6.4
5.09	5.19	-0.10	- 1.9
4.18	3.60	0.58	13.6
4.02	4.87	-0.85	-21.1
3.15	4.00	-0.85	-23.6
3.60	2.99	0.61	17.1
4.65	4.22	0.33	7.0
8.38	9.61	-1.23	-14.8
16.61	12.89	3.27	19.2
17.91	15.04	2.87	15.4
19.64	14.32	5.32	25.4
10.61	10.64	-0.03	- 0.03
14.14	12.17	1.97	13.1
15.00	13.50	1.50	10.0
11.20	11.26	-0.06	- 0.5
11.94	11.64	0.30	2.7
14.09	12.20	1.89	13.7
19.74	15.53	4.21	22.3
11.17	9.46	1.61	14.5
11.97	10.73	1.24	10.1
7.83	8.95	1.12	14.7
9.89	9.41	0.45	4.8
6.93	8.28	-1.35	-19.4
9.28	9.00	0.28	3.1
12.54	11.47	1.07	9.1

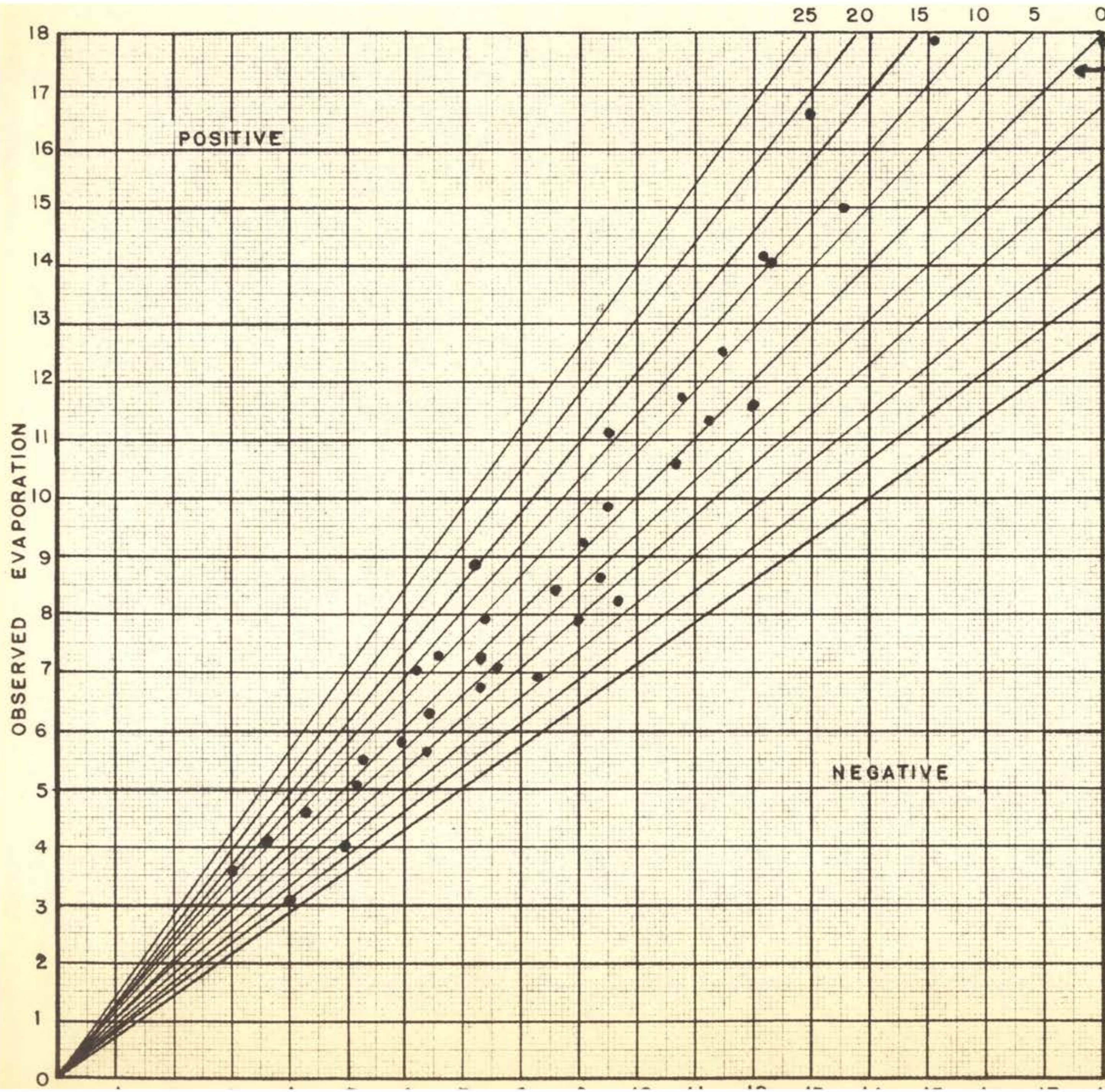

FIGURE 6

CHART PORTRAYING POSITIVE AND NEGATIVE DEVIATIONS FROM LINE $E_o = E_c$

equation. An investigation of Tables III, IV, V, and VI reveals that the following ranges exist for the variables considered:

$$T = 38.1^\circ \text{ to } 83.4^\circ, \text{ Fahrenheit}$$

$$P = 0.00 \text{ to } 7.9, \text{ inches}$$

$$W = 918 \text{ to } 5500, \text{ miles}$$

$$E = 1.90 \text{ to } 15.55, \text{ inches}$$

When the minimum values of the variables are substituted into the evaporation equation, the result is negative, signifying a gain in depth of water rather than a loss. Howsoever, these minimum values did not exist for the same station for the same month and a negative result did not appear in the computation of a representative sample of 50 observations drawn from the climatological records.

Also, if the mean value of the variables are substituted into the evaporation equation, the results again indicate a gain rather than a loss in the depth of water (Table XI). The existence of this apparent paradox suggests that the line formed by graphing the equation should go

TABLE XI

MONTHLY MEAN VALUE OF VARIABLES CONSIDERED IN THIS STUDY

Variable	Mean Monthly Value
Temperature.	65.827° Fahrenheit
Precipitation.	2.886 inches
Wind Movement.	2853.144 miles
Evaporation.	7.579 inches

through the origin, rather than some other point on the axis, and indicates that the total relationship between the variables and the evaporation process is curvilinear. However, for the range of E computed by the use of the climatological records, the relationship is linear.

Application of the Formula

The evaporation formula derived in Chapter III was of the form:

$$E = \frac{220T - 123P + W - 9390}{1000}$$

This formula was applied to 50 observations with the results being compared with the observed evaporation in Table X. In the same table, the deviations, in percent, of the computed evaporation from the actual observed evaporation were computed and these were plotted in Figure 6.

In the present form, the evaporation formula can be applied to data observed only at stations recording wind movement. To widen the applicability of the equation, in order that it might be used at all Weather Bureau weather stations in Oklahoma, it became desirable to eliminate the wind movement as a variable. This becomes feasible because the wind factor shows a very low correlation with evaporation.

The procedure followed in the elimination of the wind factor from consideration was accomplished by the use of Gauss Multipliers.[3] The resulting equation by the use of this method being:

$$E = \frac{206T - 175P - 5483}{1000}$$

where E is the monthly evaporation from a Class A pan in inches, T is the mean monthly temperature, and P is the total monthly precipitation in inches. For simplicity in computing the evaporation from this equation, an alignment chart has been constructed (Figure 7).

The method of solution using this chart is simple. First, determine the total monthly precipitation and the mean monthly temperature; next,

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[3]This method of solution is lengthy and will not be explained here. An excellent discussion explaining the method is included in G. W. Snedecor, pp. 364-371.

by use of a straight edge project a line connecting these values to the evaporation line and read off the monthly evaporation in inches from the index on the right.

For example, suppose a rainfall of 10 inches and a mean monthly temperature of 73.5° F. Align the straight edge on 10 inches of precipitation, P column, to 73.5 on the T column and read the evaporation, 8 inches, from the E column.

To further increase the use of these evaporation formulas, their connotation has been modified to include computation of yearly evaporation totals. These forms are simply:

$$E = \sum_{\text{Jan.}}^{\text{Dec.}} \frac{220T - 123P + W - 9390}{1000}$$

for use with the three factors considered originally in this study, and:

$$E = \sum_{\text{Jan.}}^{\text{Dec.}} \frac{206T - 175P - 5483}{1000}$$

for the shorter formula. Where $\sum$ is the sum of the monthly evaporation amounts obtained by applying the evaporation formula once for each month of the year. This method is somewhat arduous if the longer equation is used. However, with the use of the alignment chart, prepared from the shorter formula, the procedure is relatively rapid.

By use of the shortened formula and its corresponding alignment chart a series of evaporation maps for Oklahoma were prepared. These charts include the average Oklahoma evaporation during the coldest month, January, in inches (Figure 8); the average Oklahoma evaporation during hottest month, July, in inches (Figure 9); the average seasonal evaporation, April through October, for Oklahoma, in inches (Figure 10); and the mean annual evaporation for Oklahoma (Figure 11).

ALIGNMENT CHART FOR EQUATION $E = \frac{206T - 175P - 5483}{1000}$

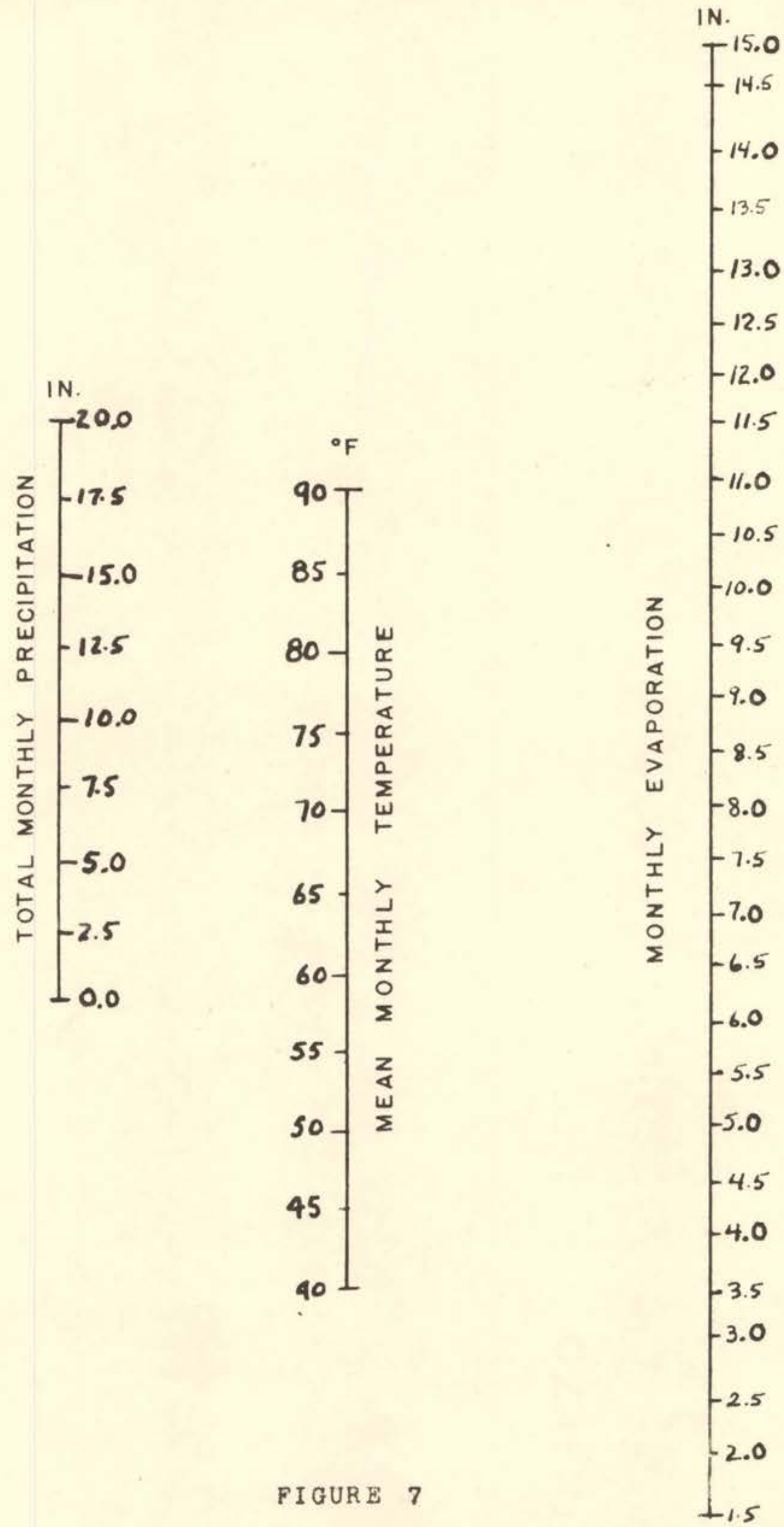
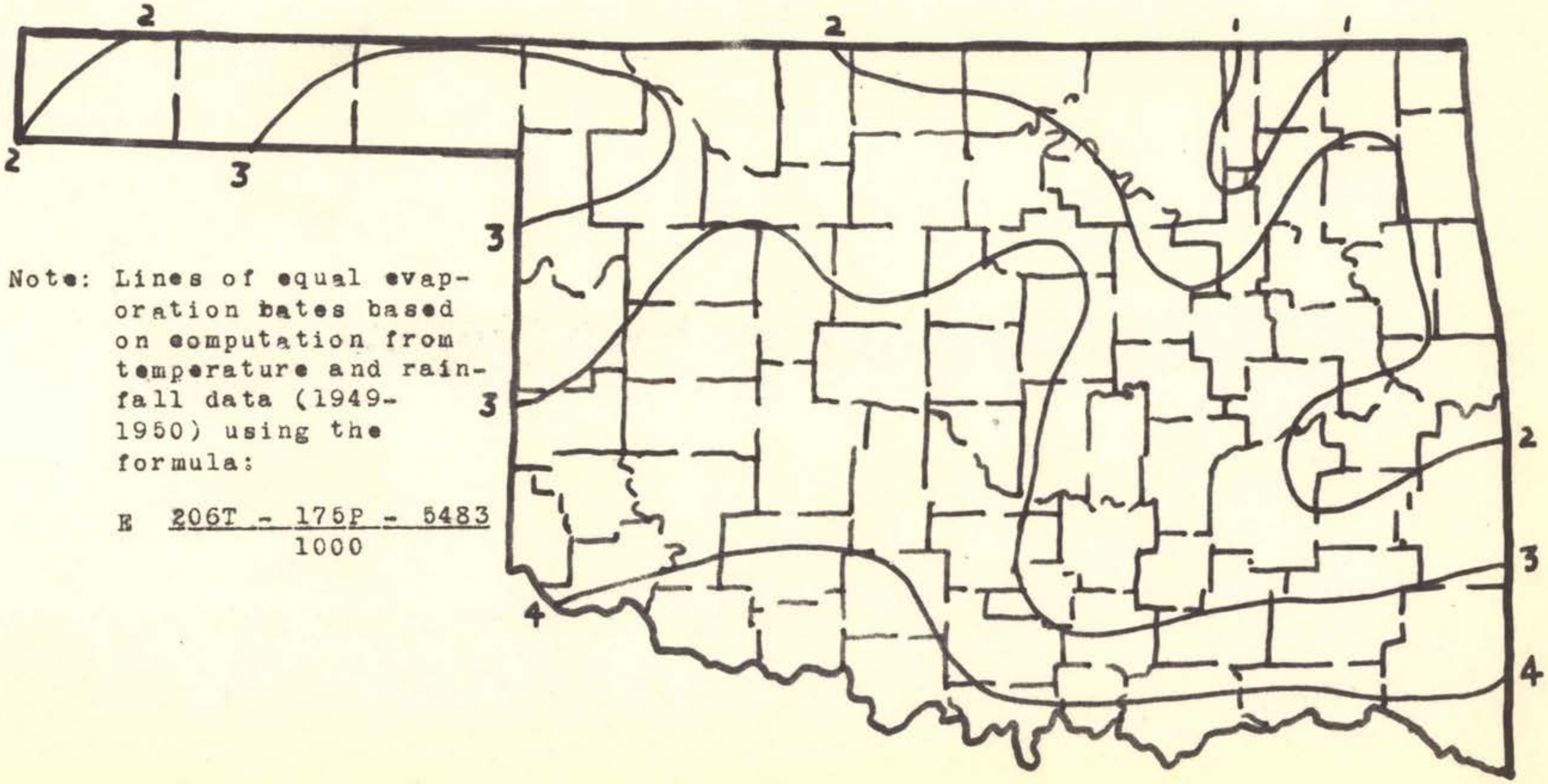


FIGURE 7

AVERAGE OKLAHOMA EVAPORATION DURING COLDEST MONTH (JANUARY) IN INCHES

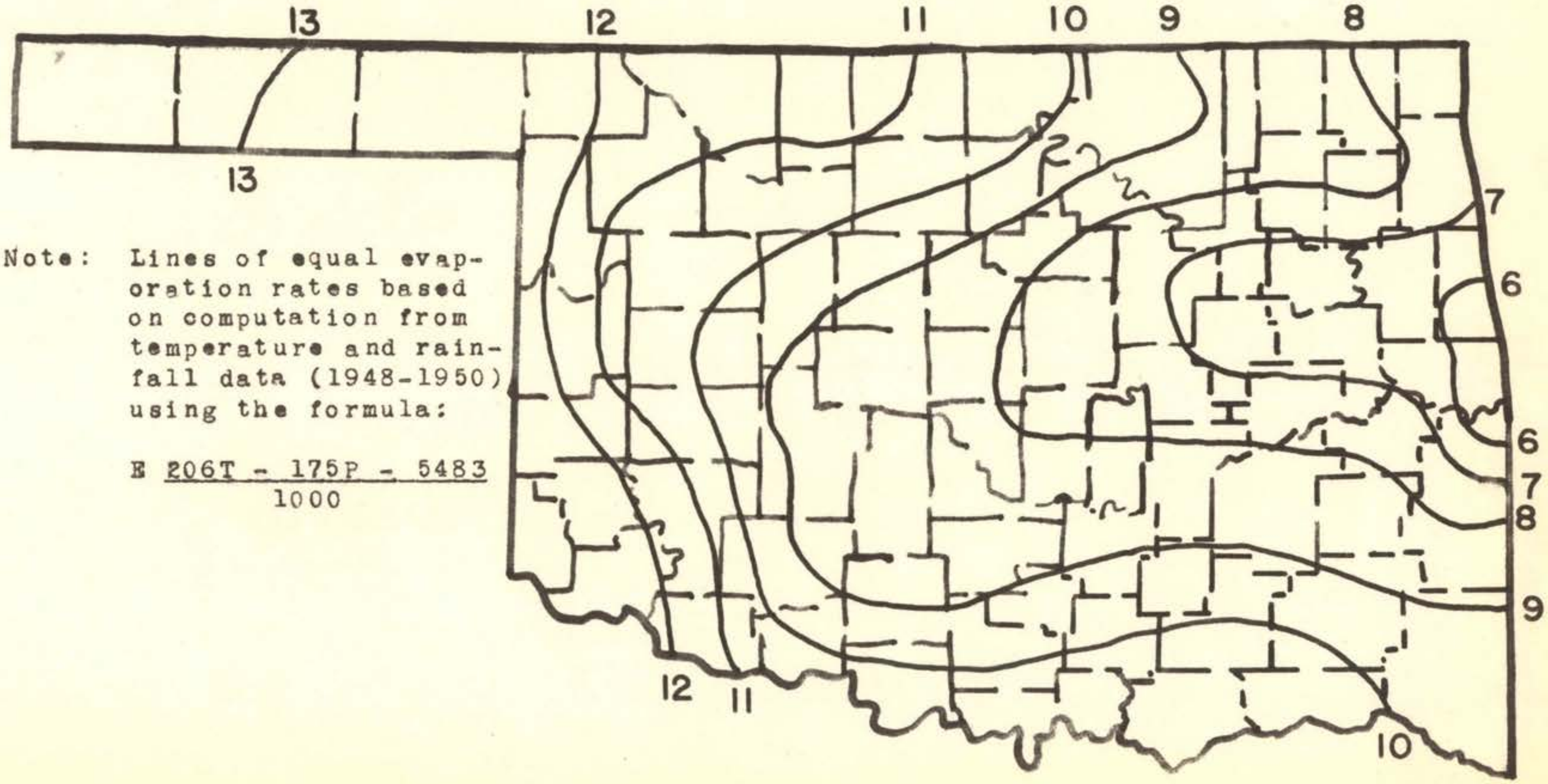


Note: Lines of equal evaporation bates based on computation from temperature and rainfall data (1949-1950) using the formula:

$$E \frac{206T - 175P - 5483}{1000}$$

FIGURE 8

AVERAGE OKLAHOMA EVAPORATION DURING HOTTEST MONTH (JULY) IN INCHES

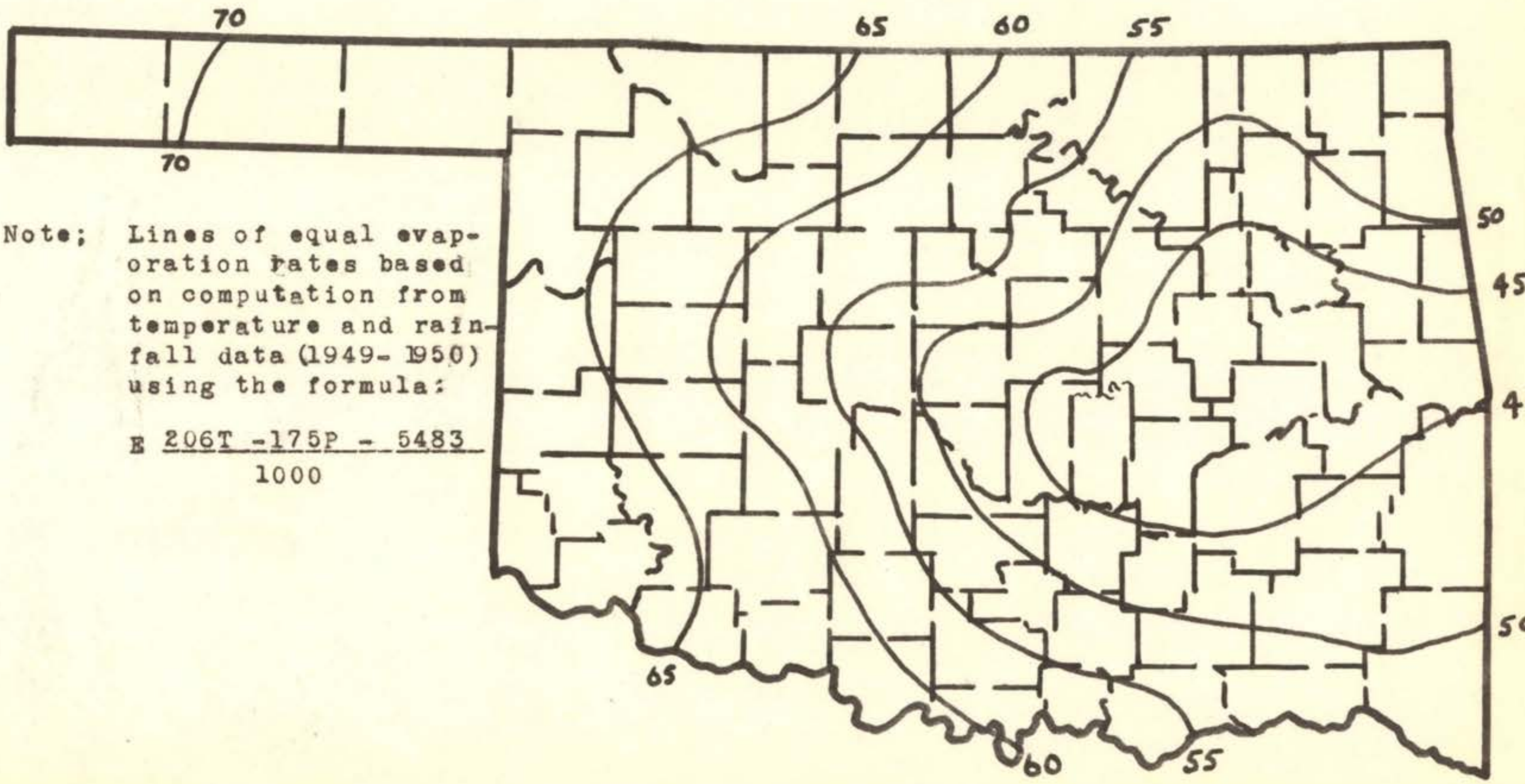


Note: Lines of equal evaporation rates based on computation from temperature and rainfall data (1948-1950) using the formula:

$$E \; \frac{206T - 175P - 5483}{1000}$$

FIGURE 9

AVERAGE SEASONAL EVAPORATION (APRIL THROUGH OCTOBER) FOR OKLAHOMA (INCHES)

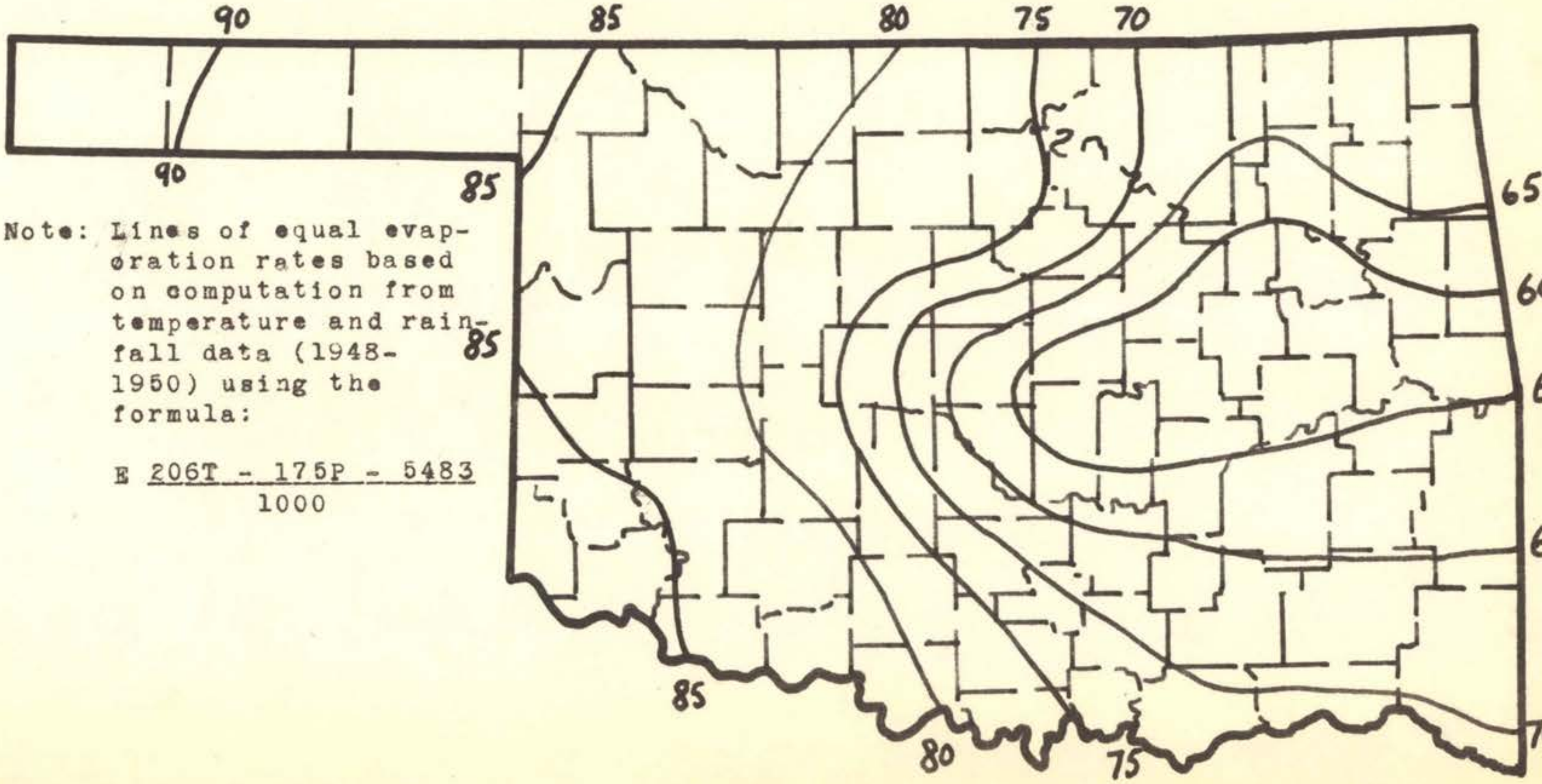


Note; Lines of equal evaporation rates based on computation from temperature and rainfall data (1949- 1950) using the formula:

$$E = \frac{206T - 175P - 5483}{1000}$$

FIGURE 10

OKLAHOMA - MEAN ANNUAL EVAPORATION IN INCHES



Note: Lines of equal evaporation rates based on computation from temperature and rainfall data (1948-1950) using the formula:

$$E\ \frac{206T - 175P - 5483}{1000}$$

FIGURE 11

A view of these charts reveals the pattern of evaporation in Oklahoma, with the total amounts increasing from east to west. This is particularly significant in that precipitation increases in approximately the opposite direction. Hence, the toll of evaporation is highest in the areas that can least afford it.

The chart portraying the average January evaporation has a pattern different from the other charts. In this case the minimum values occur to the Northeast and Northwest with the amount of evaporation increasing to the South as would be expected from the discussion in Chapter II and the results of this experiment.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Within this study an attempt has been made to evaluate the program of the United States Weather Bureau in Oklahoma, to determine the relationships existing between the climatological observations now recorded by co-operative observers of the Weather Bureau, and to derive a rational formula for the computation of evaporation from water surfaces in Oklahoma, based on existing climatological records.

Conclusions

Two high coefficients of correlation were obtained from the analysis. There were the temperature and evaporation (0.8336) and the multiple correlation coefficient for the entire experiment (0.9202). The size of these correlations with respect to perfect correlation leads one to believe that the equations derived by this analysis will give satisfactory evaporation estimates.

The series of evaporation maps in Chapter IV, obtained by use of the shortened equation, were compared with existing evaporation maps based on actual evaporation data and displayed a high degree of similarity. This comparison further proves the validity of the correlation coefficients obtained from the regression analysis.

The evaporation formula derived in this study gives the user an excellent opportunity to estimate evaporation. This formula is not rigorously correct for all physical situations which may develop, however.

This shortcoming is due partially to the character of the analysis in which the mean, rather than the actual, values predominated.

This error, however, is not as serious as might be first imagined. The purpose of the formula was to provide a method to estimate water losses by evaporation on the basis of climatological data for Oklahoma where no evaporation data are available. This has been done. Furthermore, a practical measurement of evaporation under a given set of conditions can be made only after the local variables have been analyzed. For example, evaporation from a given field would necessarily be controlled to a large extent by the amount of water present, type of soil, conditions of soil surface, and vegetative surface as well as other variables. Although the formula expresses evaporation in inches from an exposed water surface, its most practical application should be to serve as an index of evaporation from a variety of sources.

Figure 6 shows the relationship between the observed values of evaporation, E_o, and the corresponding computed values, E_c. Were the two values identical, the connection of their points would result in a straight line ($E_o = E_c$) having a slope of 45°. The lines adjacent to this line of perfect correlation are percentage lines estimating the error or discrepancy between the two values. The use of these lines enables one to limit application of the formula to his own particular degree of accuracy.

Recommendations

The results of this study indicate that evaporation can be predicted on the basis of present climatological data. However, more exact results might be obtained if the following action is taken: (a) facilities be installed at all evaporation measurement sites in Oklahoma administrated by the United States Weather Bureau for a quantitative measurement of the amount of moisture present in the immediate atmosphere; (b) these same sites should be equipped with maximum and minimum thermometers to record the temperature of the evaporating fluid as well as the free air temperature, [The present system of recording the temperature of the air approximately four feet higher than the evaporation pan surface does not truly represent the characteristics of the evaporation process.]; and (c) the establishment of two additional evaporation stations in the Southcentral and Southeastern sections of Oklahoma to provide a more complete state coverage.

In the course of the analysis, two additional studies were recognized. Should these studies be completed, the hydrologic cycle of Oklahoma could be more easily interpreted.

These studies are the analysis of the rainfall-runoff relationship in Oklahoma and the derivation of an evaporation formula using variables, presently recorded at climatological stations, which could be controlled throughout the course of the experiment.

The results of the first study would be a means to analyze the precipitation-runoff characteristics of various drainage basins, and a method for the determination of the storage potential of the drainage basin.

The second study would result in an evaporation formula, rigorously correct, based on the present system of climatological observations, which, when modified by the addition of the variable of relative humidity, as recommended within, could evaluate and conceivably justify the addition of this variable as a climatic element measured by co-operative stations.

The results of this study are a method of computation of evaporation which can be used in any section of Oklahoma where the monthly precipitation and temperatures are known. This will allow the computation of evaporation for areas previously neglected because of the lack of such a rational expression. The formulas, derived within, can be used with confidence in estimating the evaporation from water bodies, and can give the user an index of the amount of water lost from other surfaces. The degree of accuracy of the formulas are greatest for variable measures which are near the mean values of the variables considered (Table XI), but can be applied for any situation if the deviations plotted as percentages in Figure 6 are recognized.

The shortage of available water has been recognized in Oklahoma and much has been written about it. However, little has been done to correct this situation. It is hoped that the results of this study will fill a gap in the missing data and stimulate further research on the hydrologic cycle.

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